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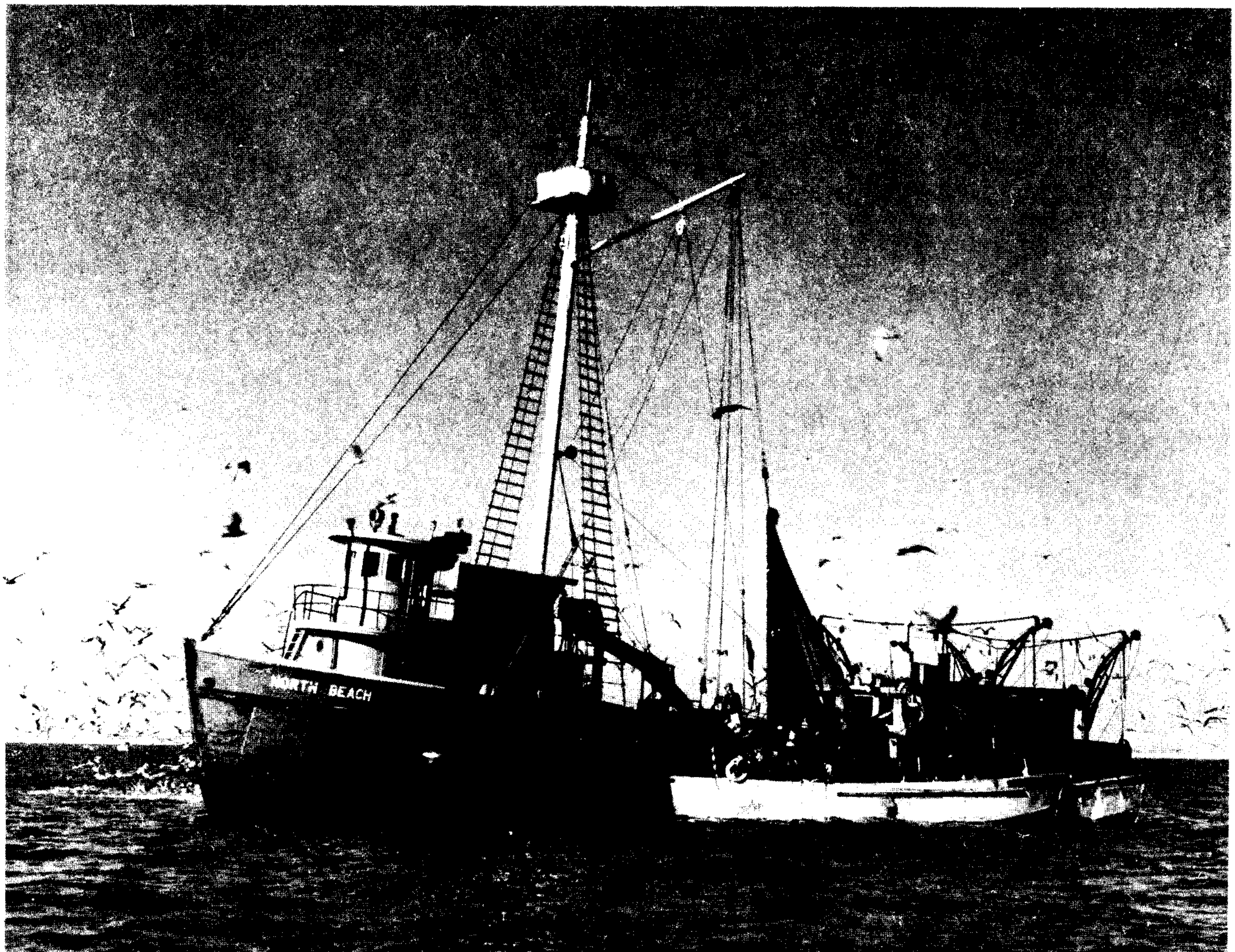

Menhaden

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On the cover: A menhaden fishing scene.

Special Issue — *53(4), 1991*

Menhaden: The Resource, the Industry, and a Management History

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MENHADEN: THE RESOURCE, THE INDUSTRY, AND A MANAGEMENT HISTORY

A Special Issue of the *Marine Fisheries Review*

Preface

DOUGLAS S. VAUGHAN

Four species of menhaden, *Brevoortia* spp., are found along the Atlantic and Gulf of Mexico coasts of the United States. The Atlantic menhaden, *B. tyrannus*, is found from Nova Scotia, Can., to West Palm Beach, Fla.; the yellowfin menhaden, *B. smithi*, is found from Cape Lookout, N.C., to the Mississippi River Delta, La.; the Gulf menhaden, *B. patronus*, is found from Cape Sable, Fla., to Veracruz, Mex.; and the finescale menhaden, *B. gunteri*, is found from the Mississippi River Delta, La., to Campeche, Mex.

Menhaden are euryhaline species that inhabit coastal and inland tidal waters. Spawning occurs principally at sea (in northern areas some spawning occurs in bays and sounds). Eggs hatch at sea and the larvae are moved to estuaries by ocean currents where they metamorphose and develop as juveniles.

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Menhaden form large surface schools susceptible to purse seines which are now the principal fishing gear. Major fisheries for Atlantic and Gulf menhaden exist on each coast (Fig. 1). Although neither fishery is directed toward the yellowfin or finescale menhaden, both may be part of these other catches to a small degree. During the 1980s, the combined landings for the menhaden reduction fisheries comprised about 40% of all U.S. commercial landings, ranging between 934,000 t and 1,342,000 t, with Gulf menhaden landings representing between two-thirds and three-fourths of the total. Menhaden are processed primarily at reduction plants for fish meal, oil, and solubles. The meal and solubles are used mostly in poultry and livestock feeds, and increasingly in aquaculture, while the oil is used in paints and as an edible oil in Europe and Canada. Smaller purse-seine menhaden fisheries for bait (e.g., crab and lobster) are found on both coasts.

The National Marine Fisheries Service (formerly Bureau of Commercial Fisheries) has maintained records of daily vessel landings and fishing activity since 1940 on the Atlantic coast and since 1946 on the Gulf coast. Sampling for age and size of menhaden landed has been conducted by staff in the NMFS menhaden research program since 1955 on the Atlantic coast and since 1964 on the Gulf coast. Captain's daily fishing reports containing data on individual menhaden purse-seine sets have been collected on both coasts since 1978. In addition, extensive mark-recapture studies (using internal ferromagnetic tags) on adult and juvenile Atlantic and Gulf menhaden have been conducted since the late 1960's. Also, studies on the biology and estuarine distribution of juvenile menhaden have been conducted along the U.S. Atlantic and Gulf coasts since the early 1960's. These studies culminated in extensive juvenile abundance surveys along both coasts during the 1970's.

Management of Atlantic and Gulf menhaden fisheries is by the respective states and coordinated through the Atlantic and Gulf States Marine Fisheries Commissions. State, industry, and Federal inter-

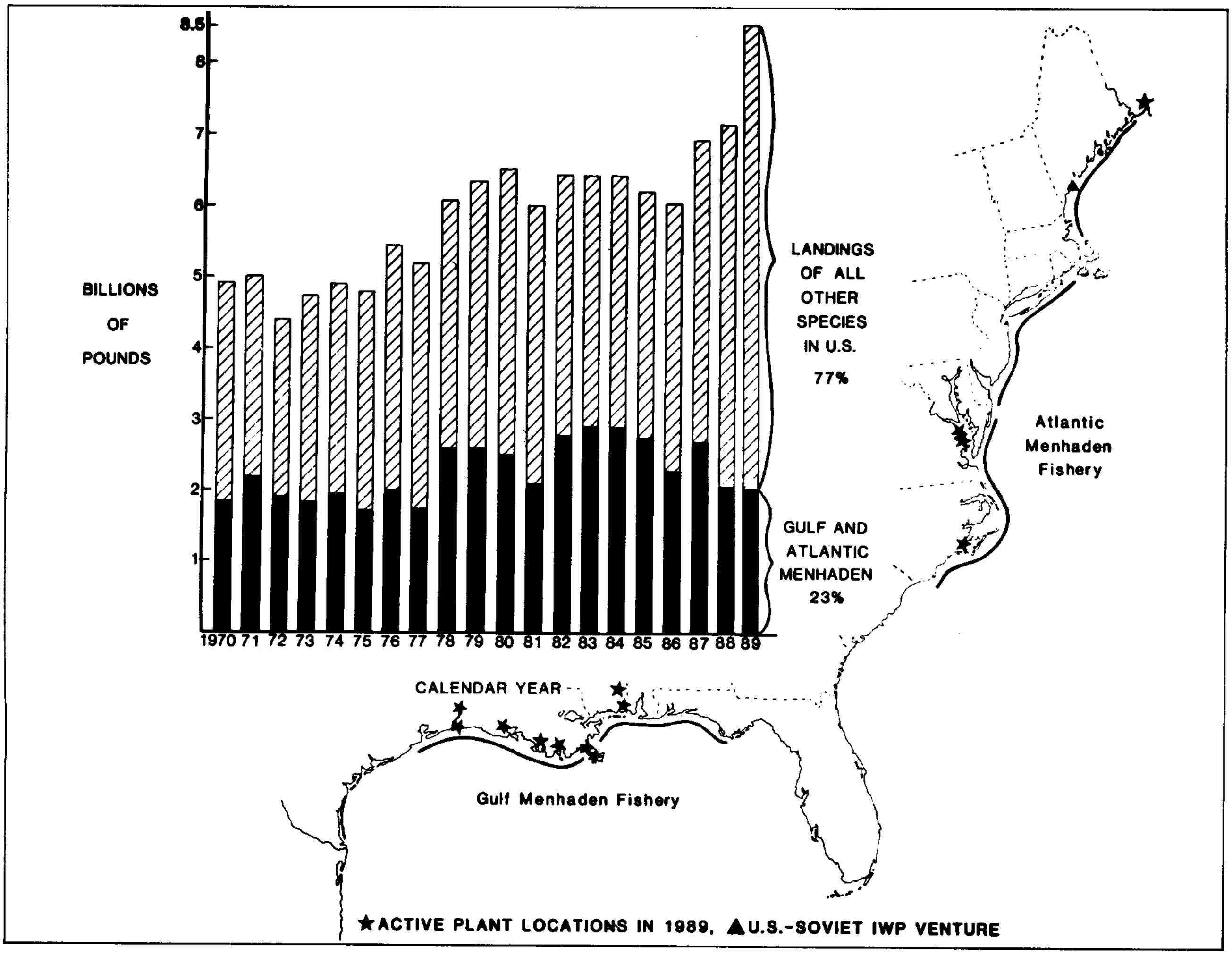

Figure 1.—Gulf and Atlantic menhaden contribution to total U.S. commercial fisheries landings during the calendar year, 1970-87.

ests are represented on the Atlantic and Gulf Menhaden Advisory Committees as part of the interstate commission fishery management process. Information from NMFS is provided to these groups, including stock assessments on these species. Coastwide management plans have been prepared for both Atlantic and Gulf menhaden with recent updates for both species.

This special issue of the *Marine Fisheries Review* provides an historical perspective on the menhaden resource and fisheries. These papers summarize information on menhaden biology, environmental influences on recruitment, results of tagging studies, the fisheries, current and potential products from menhaden, recent assessments of stock status, and describe management interactions including a comparison of management options for the Atlantic menhaden. These papers draw on previously published material and on current research. They are intended to help define "the state of our knowledge" and provide guidance in developing future studies to improve our understanding of menhaden biology and population dynamics.

Population Biology and Life History of the North American Menhadens, *Brevoortia* spp.

DEAN W. AHRENHOLZ

Introduction

Menhaden are members of the world-wide family Clupeidae, one of the most important families of fishes both economically (Hildebrand, 1963), and ecologically. Clupeids are characteristically very numerous and form large, dense schools which enhance our ability to harvest them. Many of the species are filter feeders, being either primary consumers, feeding on phytoplankton, or secondary consumers, feeding on zooplankton, or both. Many clupeids are in turn prey for various piscivorous predators through virtually their entire lives. Life history patterns for this family of fishes include species which can complete their entire life cycle in either fresh or marine waters, or are anadromous species, or marine migratory (estuarine dependent) species.

The large-scaled menhadens, the Atlantic menhaden, *Brevoortia tyrannus*, and the Gulf menhaden, *B. patronus*, have received considerable attention in fishery science research due to their large population sizes and resulting economic and ecological importance. The small-scaled menhadens, the yellowfin menhaden, *B. smithi*, and the finescale menhaden, *B. gunteri*, are less numerous and have received far less consideration in the scientific literature. The contrast in relative importance is quite marked. On one extreme, the purse-seine reduction fishery (to fish meal and oil) for Gulf menhaden was the largest U.S. fishery by weight from 1963 through 1988, and Atlantic menhaden purse-seine reduction landings, currently one-third to two-thirds those for Gulf menhaden, were the largest for the U.S. from 1947 to 1962. On the other extreme, finescale menhaden are apparently not directly sought by any recognized fishery, and yellowfin menhaden (and their hybrids) are only harvested by specialized bait fisheries on both coasts of Florida. The following is a general description of the population biology and life history of these four North American menhaden species.

ABSTRACT—Four recognized species of menhaden, Brevoortia *spp., occur in North American marine waters: Atlantic menhaden,* B. tyrannus; *Gulf menhaden,* B. patronus; *yellowfin menhaden,* B. smithi; *and finescale menhaden,* B. gunteri. *Three of the menhaden species are known to form two hybrid types. Members of the genus range from coastal waters of Veracruz, Mex., to Nova Scotia, Can. Atlantic and Gulf menhaden are extremely abundant within their respective ranges and support extensive purse-seine reduction (to fish meal and oil) fisheries. All menhaden species are estuarine dependent through late larval and juvenile stages. Depending on species and location within the range, spawning may occur within bays and sounds to a substantial distance offshore. Menhaden are considered to be filter-feeding, planktivorous omnivores as juveniles and adults. Menhaden eggs, immature developmental stages, and adults are potential prey for a large and diverse number of predators. North American menhadens, including two hybrids, are hosts for the parasitic isopod,* Olencira praegustator, *and the parasitic copepod,* Lernaeenicus radiatus. *Although the data are quite variable, a dome-shaped Ricker function is frequently used to describe the spawner-recruitment relationship for Atlantic and Gulf menhaden. Each of these species is treated as a single stock with respect to exploitation by the purse-seine reduction fishery. Estimates of instantaneous natural (other) mortality rates are 0.45 for Atlantic menhaden and 1.1 for Gulf menhaden.*

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Geographic Ranges

Reintjes (1969) summarized the geographic ranges for the four menhaden species. Atlantic menhaden are seasonally found from Nova Scotia, Can., to southeastern Florida, near West Palm Beach. Gulf menhaden range from southwestern Florida, near Cape Sable, to Veracruz, Mex. Yellowfin menhaden overlap the ranges of all three other menhaden species and are found from Cape Lookout, N.C., to the Mississippi River Delta. Finescale menhaden overlap the ranges of both the Gulf and yellowfin menhaden, and are found from just east of the Mississippi River Delta (Turner, 1971) to Campeche, Mex.

The numbers of Gulf menhaden relative to numbers of yellowfin menhaden become reduced proceeding southward on the Gulf of Mexico coast of Florida. There appears to be a similar distribution pattern for relative numbers of Atlantic and yellowfin menhaden proceeding southward along the Atlantic coast of Florida. The coastal area between West Palm Beach and Miami, Fla., where menhaden are relatively rare (Dahlberg, 1970), geographically separates the Atlantic menhaden from the Gulf menhaden, as well as apparent eastern and western populations of yellowfin menhaden.

A large amount of hybrid introgression occurs between Atlantic and yellowfin menhaden on the Atlantic coast of Florida, and Gulf and yellowfin menhaden on the Gulf coast of Florida. Areas with pure strains of yellowfin menhaden are yet to be defined. As the relative density of Gulf menhaden decreases proceeding southward, the number of Gulf × yellowfin menhaden (*B. patronus* × *B. smithi*) hybrids increases along with pure strains of yellowfin. For example, Turner (1969) reported that collections of menhaden from Panama City to Cedar Keys, Fla., consisted of 94% Gulf menhaden and 6% yellowfin menhaden, while samples from farther south, Tampa Bay to Cape Sable, Fla., were 7% Gulf menhaden, 56% yellowfin menhaden, and 37% Gulf × yellowfin hybrids. Hettler (1968) reported on two collections made along the southern Gulf coast of Florida; one near Naples consisted of 17% Gulf menhaden, 9% yellowfin menhaden, and 74% Gulf × yellowfin hybrids, and the other from near Sanibel Island consisted of 5% Gulf menhaden, 54% yellowfin menhaden, and 41% Gulf × yellowfin hybrids. A similar situation apparently exists on the east coast of Florida with the distributions of Atlantic and yellowfin menhaden and the Atlantic × yellowfin hybrids; for example, the menhaden gill-net fishery in Indian River, Fla., is dominated by yellowfin menhaden and the Atlantic × yellowfin hybrids (Dahlberg, 1970).

Table 1.—Distinguishing and comparative characteristics of North American coastal menhadens (modified from Dahlberg, 1970).

Character	Large-scaled menhaden		Small-scaled menhaden	
	B. tyrannus	*B. patronus*	*B. smithi*	*B. gunteri*
Frontal groove	Complete	Complete	Absent	Absent
Lateral spots	Usually present above and below the level of shoulder spot	Usually present above and below the level of shoulder spot	Absent	Absent
Ventral fin	Middle rays and sometimes inner rays equal in length to outer rays	Inner rays equal to or longer than outer rays	Inner rays about one-half to two-thirds length of fin	Inner rays about one-half to two-thirds length of fin
Scale pectinations[1]	Pointed, length medium or long	Pointed	Rounded tip, shorter	Rounded tip, shorter
Body mucus[2]	Copius	Copius	Sparse	Sparse
Flesh[2]	Soft	Soft	Firm	Firm
Ovarian color	Yellow	Yellow	White	?
Lateral scale rows	43-53 (40-58)	42-48	57-73 (54-80)	65-72 (60-76)
Opercular striations	Prominent (12-31)	Prominent (13-25)	Faint or absent (0-15)	Faint or absent (0-18)
Predorsal scales	35-44 (33-46)	29-37 (28-39)	39-51 (37-56)	40-49 (39-52)
Vertebrae	46-48 (44-49)	44-46 (43-47)	44-45 (43-46)	42-43 (41-43)
Ventral scutes	31-34 (29-34)	29-31 (28-32)	30-32 (29-34)	28-30 (27-31)

[1] Older adults.
[2] Fresh specimens.

Species Characteristics

Menhaden are generically distinguished from other clupeids by their relatively large heads, pectinated scales, absence of teeth (beyond juvenile stages), and by their dorsal fin being over the interval between the pelvic and anal fins (Reintjes, 1969; Hildebrand, 1963). The two large-scaled menhaden species can be separated from the two small-scaled species by a variety of characteristics (Table 1). Fresh specimens can be separated simply by feel, as the large-scaled menhadens have large amounts of body mucus and relatively soft flesh, while the small-scaled species have relatively small quantities of body mucus and their flesh is firm. Additionally, the large-scaled species possess a frontal groove, accessory lateral spots beyond the large shoulder spot, and have larger and fewer scales. The small-scaled menhadens lack the former characteristics and have smaller and more numerous scales. Gulf menhaden have a deeper (more convex) body shape and fewer predorsal scales, vertebrae, and ventral scutes than their Atlantic congener (Table 1, Fig. 1, 2). The yellowfin menhaden can be separated from the finescale menhaden by the yellowfin's greater number of vertebrae and ventral scutes, and relatively smaller

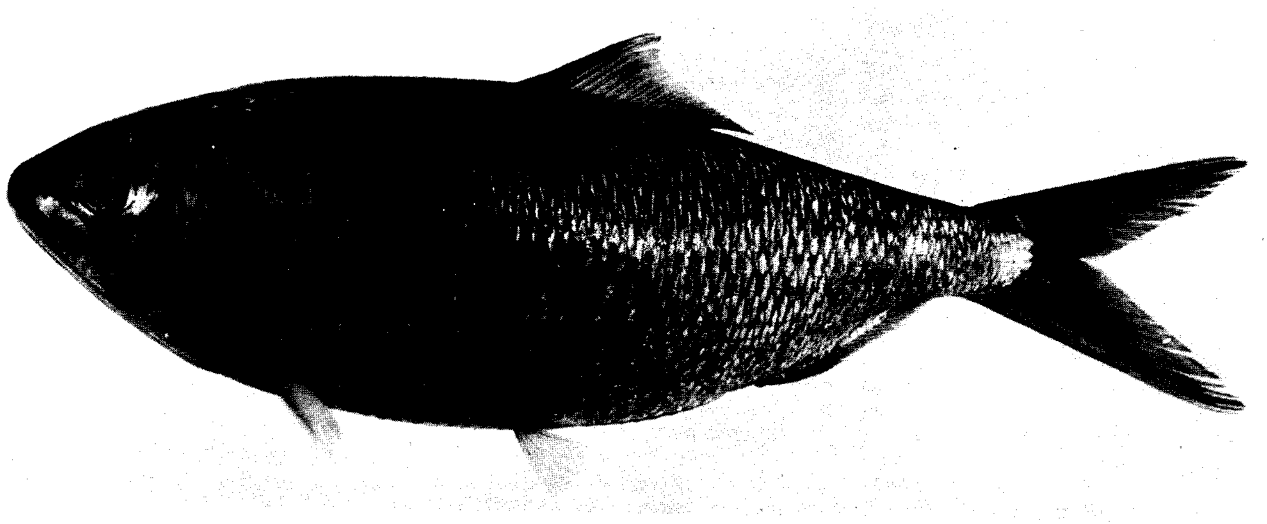

Figure 1.—Adult Atlantic menhaden, 250 mm FL (J. W. Reintjes photo).

Figure 2.—Adult Gulf menhaden, 167 mm FL (R. B. Chapoton photo).

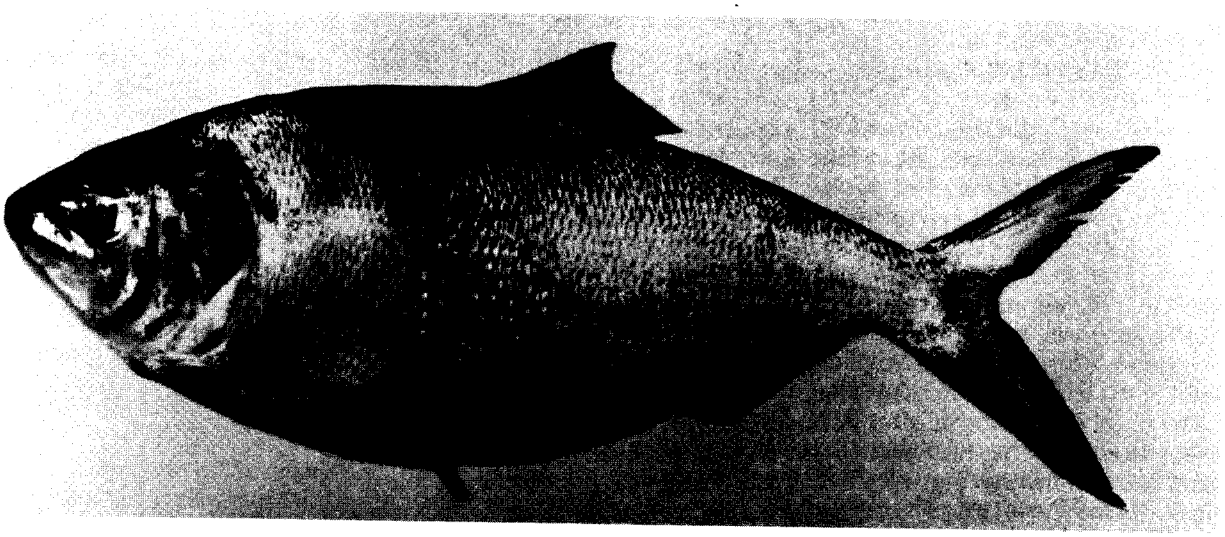

Figure 3.—Adult yellowfin menhaden, 300 mm FL (J. W. Reintjes photo).

head (Table 1, Fig. 3, 4). More detailed descriptions are available from Dahlberg (1970) and Hildebrand (1963). Dahlberg (1970) also provides divergent characteristics between the Atlantic and Gulf populations of yellowfin menhaden.

The morphological and morphometrical appearances of the large-scaled menhaden and yellowfin menhaden hybrids are intermediate to those for the parents (Dahlberg, 1970) (Fig. 5). The presence of a gradient of characteristics between the parental types suggests back-crossing also occurs. Back-crossing with either parental population will be predominantly by male hybrids, as they dominate the hybrid population. A self-sustaining population of hybrids is unlikely due to the preponderance of males. Hettler (1968) found no female hybrids (*B. patronus* × *B. smithi*), while Turner (1969) reported finding 4 females out of 390 hybrids examined. Dahlberg (1970) discovered one female hybrid (*B. tyrannus* × *B. smithi*) from an unknown number of hybrids examined on the Atlantic coast, and found no females among Gulf hybrids.

Hybrids of *B. gunteri* × *B. patronus* (finescale × Gulf menhaden) and *B. gunteri* × *B. smithi* (finescale × yellowfin menhaden) have not been reported. Although the ranges of the three species overlap, yellowfin and finescale menhaden are not abundant in the area of overlap (the Mississippi Delta region). Except for the southeastern Texas coast, finescale menhaden are apparently not abundant in U.S. Gulf coastal waters where Gulf menhaden predominate. Definitive studies on finescale menhaden are lacking.

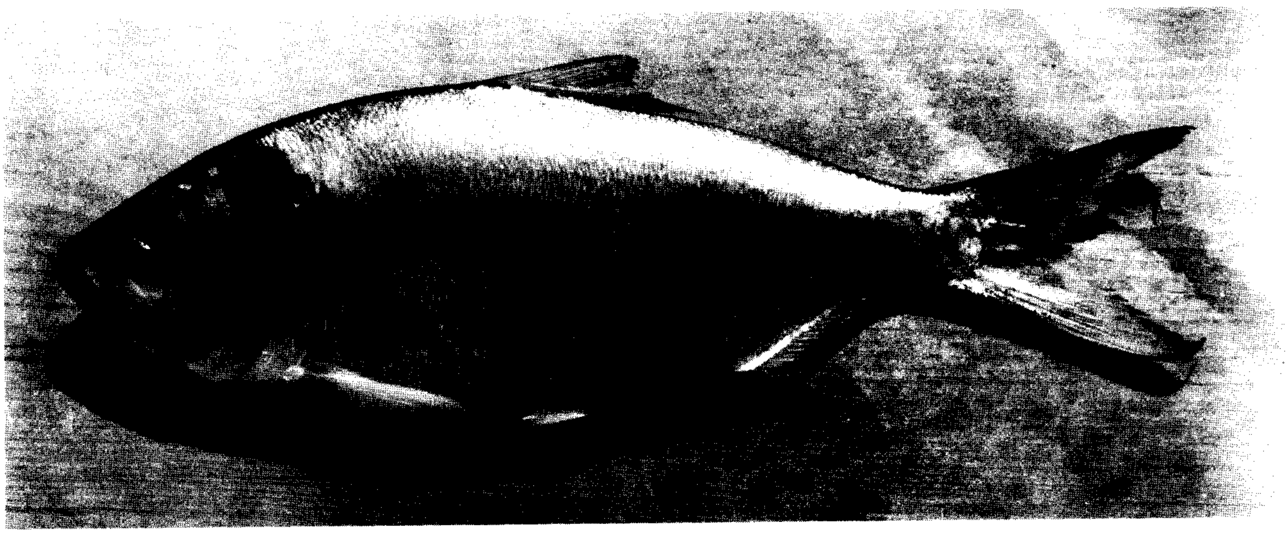

Figure 4.—Adult finescale menhaden, 320 mm FL (R. B. Chapoton photo).

General Life Cycle

Menhaden are estuarine dependent, marine migratory species. Spawning generally occurs during the cooler months in the marine environment, and larvae undergo early growth and development at sea. About 1-2 months later, those larvae that have been transported shoreward enter estuarine bays, sounds, and streams, and metamorphose into juveniles. Menhaden juveniles (young-of-the-year) normally reside in estuarine areas until the following fall or early winter when many migrate into marine waters. Adults generally occur in nearshore oceanic waters and frequently reside in large estuarine systems.

Migratory Behavior and Spawning Season

Atlantic Menhaden

Early hypotheses of the migratory behavior of Atlantic menhaden were based upon observations of schools appearing and disappearing along the U.S. Atlantic coast, and from the examination of the age and size composition of catches among fishing ports along the U.S. Atlantic coast (June and Reintjes, 1959). An analysis of the frequency and distribution of purse-seine sets contributed additional information with respect to the timing of migrations (Roithmayr, 1963). The existing knowledge of migration and distribution was further strengthened by an analysis of the age and length distributions of Atlantic menhaden in the landings (Nicholson, 1971), and finally from results of an internal, ferromagnetic tagging program (Dryfoos et al., 1973; Kroger and Guthrie, 1973; Nicholson, 1978).

During summer, Atlantic menhaden are generally distributed from northern Florida to Maine. The adult population stratifies by age and size, with the older and larger individuals farther northward and the younger and smaller fish in the southern half of the species' range. Although localized movements occur during summer, no major systematic movement occurs until September, when the more northerly portion of the population begins to migrate southward. By December, a significant portion of the adult population that was north of Chesapeake Bay during summer has moved southward to waters off the North Carolina coast. These fish are followed by large numbers of juvenile (young-of-the-year) menhaden, which have recently emigrated from nursery areas farther north. Usually by late January, menhaden schools disappear and schools disperse from nearshore surface waters of North Carolina. During March or early April, schools of adult menhaden reassemble in coastal waters and move rapidly northward. By June, the population is redistributed from Florida to Maine. Even though some Atlantic menhaden migrate north and south along the U.S. Atlantic coast, because the fish distribute themselves on the basis of size and age, the movement actually represents a seasonal expansion and contraction of the Atlantic menhaden's range.

Geotemporal aspects of spawning for this species are closely associated with the migratory behavior of the adults, and some degree of spawning activity is believed to occur during virtually every month of the year. Some fish ripen and some spawning occurs in the more northerly portions of the fishes range as the fish begin moving southward in September. Spawning continues with increasing intensity as the fish move progressively farther southward in October and November. Spawning intensity is believed to peak in waters off the North Carolina coast during winter. Spawning continues, but with decreasing levels of intensity as the fish move northward the following spring and early summer. Supporting evidence for these conclusions was obtained earlier by Higham and Nicholson (1964), subsequently by Kendall and Reintjes (1975), and later by Judy and Lewis (1983). Atlantic menhaden are believed to spawn in oceanic waters over much of the continental shelf, and in bays and sounds in Long

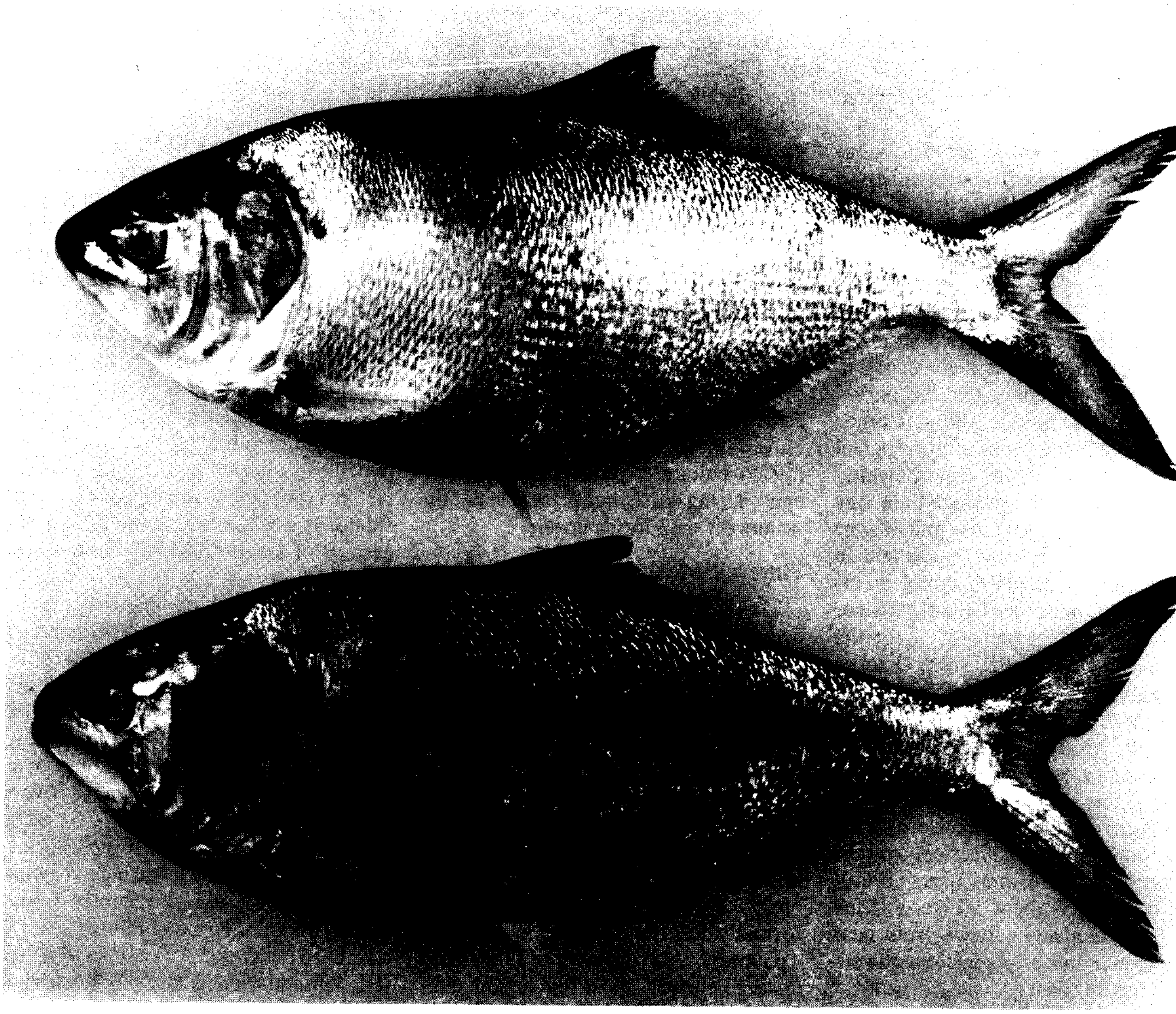

Figure 5.—Adult yellowfin menhaden (upper), 280 mm FL, and Atlantic × yellowfin menhaden hybrid (lower), 285 mm FL (J. W. Reintjes photo).

Island waters and northward (Nelson et al., 1977; Ferraro, 1980b). Evidence for recent spawning activity was based on the presence of menhaden larvae and eggs in plankton samples. Evidence of imminent spawning was also provided by the presence of near-ripe specimens in fish samples obtained from commercial purse-seine landings. However, spawning has not been directly observed in the marine environment, and running-ripe females are rarely captured.

The relative magnitude of temporal spawning activity within and between geographic regions is in part a function of the age/size structure of the spawning population. For example, with the bulk of the spawning stock in recent years consisting of late age-2 fish, relatively less spawning activity would have been expected in the New England and Middle Atlantic areas as compared to the 1950's when a broader and stronger age structure was more extant in the population (Ahrenholz et al., 1987b).

Gulf Menhaden

Gulf menhaden do not exhibit an extensive migratory pattern. During late spring and summer they distribute along the U.S. Gulf coast in nearshore waters. Beginning in October, they move offshore into deeper waters for winter. Roithmayr and Waller (1963) reported that during summer Gulf menhaden occurred in depths of 1-8 fathoms, while during winter months they were found in 4-18 fathoms east and west of the Mississippi Delta, and at 20-48 fathoms in a smaller area east and northeast of the Delta.

Results of tagging studies failed to identify any east-west component of annual migration for Gulf menhaden (Pristas et al., 1976; Kroger and Pristas, 1975); however, multiple-year juvenile tag-recovery data indicated a tendency for Gulf menhaden from the eastern and western extremes of their range to move toward the center of their range with age (Ahrenholz, 1981).

The spawning season for Gulf menhaden was determined by observations of larvae, gonadal development, and presence of eggs in plankton samples. Spawning has not been directly observed. From observations of the occurrence of larvae in Lake Ponchartrain, La., Suttkus (1956) concluded that spawning probably began in October and ceased in February; he presumed that this period could fluctuate among years. Combs (1969) concluded from a histological examination of ovaries that spawning ranged from October through February or early March. Christmas and Waller (1975), after a literature review and an examination of plankton samples collected from much of the Gulf of Mexico, concluded that spawning "...for the most part..." occurred from October through March. Shaw et al. (1985a) presented arguments and evidence for an even more protracted season.

Spawning areas have been determined by noting the geographic collection sites where Gulf menhaden eggs were taken. Based on their own collections and the work of Fore (1970) and Turner (1969), Christmas and Waller (1975) concluded that Gulf menhaden spawn from near shore to 60 miles offshore along the entire U.S. Gulf coast.

Yellowfin Menhaden

Adult yellowfin do not appear to display any systematic, annual migratory behavior. Dahlberg (1970) referred to them as "...common near shore along both Florida coasts throughout the year." He considered them an inshore or bay form (in contrast to the large-scaled menhadens). Some larger individuals are occasionally found as far north as Cape Lookout, N.C., during summer.

Spawning seasons and some spawning areas have been identified by collecting specimens for artificial spawning and rearing. For the Atlantic coast population, Reintjes (1962) began sampling near Sebastian, Fla., in November. He noted ripening males in December, several ripening females in January, and by February 8 about 25% of females were ready to spawn. Hettler's (1970) specimens from the Atlantic coast were taken from the Indian River, Fla., in February. Dahlberg (1970) concluded that the spawning season for yellowfin menhaden was February and March on both the Atlantic and Gulf coasts of Florida. His conclusion for the Gulf coast was at least in part based on Hettler's (1968) collection just north of Naples during mid-March of two ripe female yellowfin menhaden and Turner's (1969) collection of ripe females during February and March off the southern Gulf coast of Florida. Spawning may occur as early as November, as Houde and Swanson (1975) collected yellowfin menhaden eggs during this month from Atlantic waters off the Florida coast.

Finescale Menhaden

There is no evidence from which to deduce any systematic seasonal migration by the finescale menhaden other than the notation of an apparent seasonal shift of larger finescale menhaden between Texas bays (Gunter, 1945). Like the yellowfin menhaden, the finescale menhaden appears to occur more in estuarine or nearshore areas. Gunter (1945) referred to it as a brackish-water form, as opposed to the more saline Gulf menhaden, although this species was not formally described until 3 years later.

Gunter (1945) discovered a ripe male during February and a ripe female during the latter part of March, and noted that the spawning season was probably from midwinter to early spring. He also observed post-larval finescale menhaden from January to May. Simmons (1957) reported that this species spawned in the upper Laguna Madre of Texas during February. Given these observations, a spawning period of November to March appears realistic. Both Simmons (1957) and Gunter (1945) reported that spawning occurs in inside (estuarine) Texas waters.

Maturation and Fecundity

Gulf menhaden become sexually mature near the end of their second year of life (age 1) (Lewis and Roithmayr, 1981). By comparison, only a small percentage of Atlantic menhaden become sexually mature during their second year of life, while from two-thirds to nearly all are sexually mature by the end of their third year (age 2) (Higham and Nicholson, 1964; Lewis et al., 1987). Female Gulf menhaden about 150 mm FL and larger are generally sexually mature by the spawning season (Lewis and Roithmayr, 1981), while the smallest sexually mature female Atlantic menhaden are at least 180 mm FL (Lewis et al., 1987).

Age and size at maturation data is limited for the small-scaled menhadens. Gunter (1945) observed a ripe female finescale menhaden 150 mm TL, and a ripe male 125 mm TL. The smaller of the two ripe female yellowfin menhaden that Hettler (1968) found was 186 mm FL. No standing stock ova counts for either species of small-scaled menhaden are available.

Atlantic and Gulf menhaden are considered to be multiple (fractional or intermittent) spawners (Higham and Nicholson, 1964; Combs, 1969). As noted by Combs (1969), the fishes' ovaries could not contain all the developing ova if they matured at the same time. Thus, ova mature and are spawned in batches over a protracted spawning season.

The potential number of ova produced by an individual female during a spawning season has been determined (estimated) by counting the standing stock of advanced oocytes in Atlantic menhaden (Higham and Nicholson, 1964; Dietrich, 1979; Lewis et al., 1987) and Gulf menhaden (Suttkus and Sundararaj, 1961; Lewis and Roithmayr, 1981). For this technique to provide a reasonable estimate of true annual fecundity, the number of ova produced during a season must be annually determinate, like that of the multiple spawning Atlantic silverside, *Menidia menidia* (Conover, 1985), as opposed to being annually indeterminate, similar to the multiple spawning northern anchovy, *Engraulis mordax* (Hunter and Macewicz, 1985). While some workers (e.g., Lewis et al., 1987) felt that determinate fecundity is likely for the Atlantic menhaden (and thus likely for the other menhadens), this condition has not been demonstrated, nor has batch fecundity been estimated for any species of menhaden.

Fecundity estimates currently used in spawner-recruitment analyses (when number of potential eggs produced is used as a measure of spawning stock) are derived from the results of Lewis and Roithmayr (1981) for Gulf menhaden (Fig. 6). Fecundity values for the Atlantic menhaden are results of pooled data from Higham and Nicholson (1964), Dietrich (1979), and Lewis et al. (1987) (Fig. 6). These fecundity estimates are useful in stock assessment analyses because they ascribe a measure of relative reproductive value for larger (and older) fish in the population.

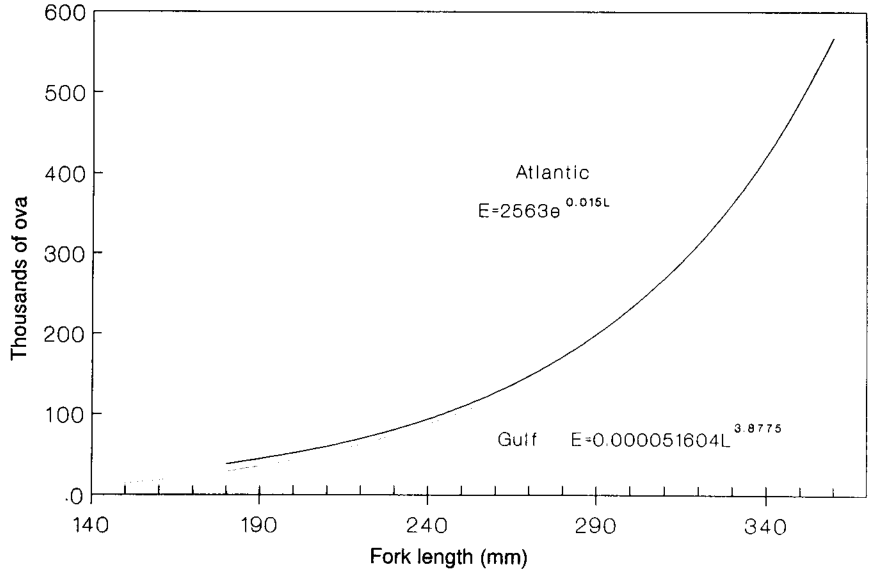

Figure 6.—Potential number of ova (in thousands) as a function of FL for Atlantic menhaden (line) and Gulf menhaden (dashes).

Description and Development of Immature Life Stages

Eggs

A description of the early life history forms of Atlantic menhaden is given by Kuntz and Radcliffe (1917). These authors collected a developmental series of ripe adults through eggs, embryos, larvae, and juveniles during summer from Woods Hole Harbor, Martha's Vineyard, and Nantucket Sound. They described the eggs as spherical in shape, highly transparent with a thin, horny egg membrane and a relatively wide perivitelline space. Each egg contained a single oil globule. Their recorded egg dimensions are summarized in Table 2.

Descriptions of eggs from other species of menhaden followed a number of years later. Reintjes (1962) described yellowfin menhaden eggs obtained on the Atlantic coast of Florida from both planktonic sampling and artificial fertilizations. Hettler (1968) described yellowfin × Gulf menhaden eggs from the Gulf coast of Florida, obtained by artificial cross fertilization. Houde and Fore (1973) described Gulf menhaden eggs from planktonic collections. An additional description of yellowfin menhaden eggs obtained from the Atlantic coast of Florida was given by Houde and Swanson (1975). Hettler (1984) described eggs obtained for laboratory-spawned Atlantic and Gulf menhaden (Table 2). Powell and Phonlor (1986) indicate that Atlantic menhaden eggs tend to be larger than those of Gulf menhaden for a particular set of conditions; however, due to dimensional overlap, menhaden eggs are not distinguishable to species with morphological characteristics (Table 2).

Egg hatching time varies as a function of temperature and species. Kuntz and Radcliffe (1917) reported incubation time for Atlantic menhaden eggs as less than 48 hours. Ferraro (1980a) developed a temperature-dependent empirical equation from which temporal estimates of duration for any stage of embryological development, including hatching, could be obtained. Reintjes (1962) reported hatching times of 46 hours from fertilization for yellowfin menhaden eggs held at temperatures of 18.5° to 19.0°C. Additional data on hatching time obtained from the study reported by Reintjes (1962) are given by Hettler (1968) as 46 hours at 18°C, 34 hours at 21°C, and 26 hours at 26°C. Hettler (1968) further reported that the yellowfin × Gulf menhaden eggs hatched in about 38-39 hours when held at 19.5 to 21.5°C. Hettler (1984) reported Gulf

Table 2.—Comparative characteristics of North American coastal menhaden eggs by species and source.

Species and source	Egg diameter (mm)	Yolk diameter (mm)	Oil globule diameter (mm)	Source of eggs
B. tyrannus				
Kuntz and Radcliffe (1917)	1.4-1.6	0.9	0.12-0.14	Planktonic
Jones et al. (1978)	1.30-1.95	0.90-1.20	0.11-0.17	?
Hettler (1984)	1.54-1.64	0.82-0.95	0.20-0.23	Laboratory reared
B. patronus				
Houde and Fore (1973)	1.04-1.30		0.08-0.20	Planktonic
Hettler (1984)	1.18-1.34[1]	0.95 (0.05)[2]	0.16-0.22[1]	Laboratory reared
B. smithi				
Reintjes (1962)	1.21-1.48	0.77-1.04	0.05-0.18	Planktonic
Reintjes (1962)	1.15-1.30	0.77-0.95	0.07-0.16	Artificially spawned
Houde and Swanson (1975)	1.21-1.34	0.80-1.19	0.12-0.17	Planktonic
B. gunteri	No data			
B. smithi × *B. patronus*				
Hettler (1968)	1.05-1.18	0.98		Artificially spawned

[1] Combined results from two spawning series.
[2] Range for spawning with larger yolks not given, mean and one standard deviation shown; range for spawning with smaller yolks 0.66-0.79 mm.

menhaden eggs hatched in 40-42 hours at 19-20°C.

Larvae

Larval development through the prejuvenile stages are described by Kuntz and Radcliffe (1917) and Lewis et al. (1972) for Atlantic menhaden, by Hettler (1984) for Gulf menhaden, and by Houde and Swanson (1975) for yellowfin menhaden. Additional information on early larval yellowfin menhaden is given by Reintjes (1962) and Hettler (1970).

The size of menhaden larvae at hatching is thought to be a function of egg size (Powell and Phonlor, 1986). Observed sizes at hatching ranged from 2.6 mm to about 3.7 mm SL (Houde and Swanson, 1975; Hettler, 1984; Powell and Phonlor, 1986). The smallest individuals were Gulf menhaden and the largest, Atlantic menhaden, with yellowfin menhaden about midrange.

The larvae are relatively undeveloped upon hatching. The mouth is not formed, the eyes are unpigmented and thus nonfunctional, and the fin rays are undeveloped (Houde and Fore, 1973; Reintjes, 1962). Depending on temperature, larval menhaden begin feeding within 2-6 days. Most of the yolk is absorbed during the prefeeding developmental period, but some may remain after the onset of feeding (Houde and Swanson, 1975). Once the yolk sac is absorbed, the larvae are slender and rodlike.

The subsequent rate of growth for each species depends on temperature and food availability. Hettler (1984) reported that larval Gulf menhaden growth averaged 0.30 mm day^{-1} for the first 90 days of rearing. He also reported that growth of yellowfin menhaden larvae averaged 0.36 mm day^{-1} through 32 days (Hettler, 1970). Houde and Swanson (1975) observed larval yellowfin menhaden growth of 0.45 mm day^{-1} for the first 20 days of rearing, albeit at a higher temperature than Hettler (1970). Additional comparative growth values were obtained by adjusting the exponential expressions given by Powell and Phonlor (1986). Growth for their Atlantic menhaden was about 0.41 mm day^{-1} and for their Gulf menhaden, 0.33 mm day^{-1} for about 18 days of rearing. Warlen (1988) reported an average rate of 0.30 mm day^{-1} over 60 days for ocean-sampled Gulf menhaden larvae.

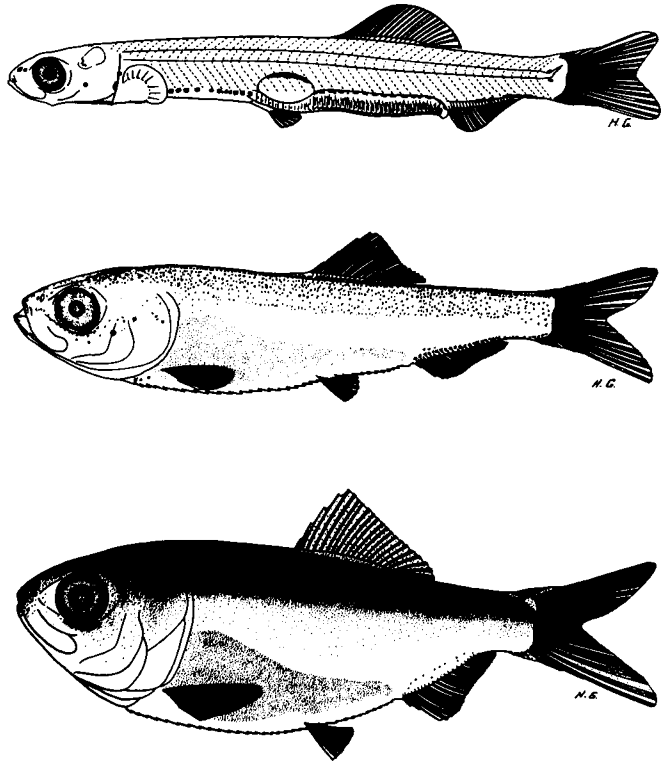

Figure 7.—Illustrations of Atlantic menhaden larva (27 mm TL), prejuvenile (32 mm TL), and juvenile (64 mm TL); upper, middle, and lower, respectively, from Lewis et al. (1972).

Atlantic menhaden larvae ranging from 14 to 34 mm FL (Reintjes and Pacheco, 1966) enter estuarine nursery areas at about 45-60 days of age (Nelson et al., 1977). Larvae are reported as entering estuaries in New England during May through October, in the U.S. Middle Atlantic from October to June, and along the U.S. South Atlantic coast from November to May (Reintjes and Pacheco, 1966; Wilkins and Lewis, 1971).

The length of the oceanic period for larval Gulf menhaden is estimated at 6-10 weeks (Deegan and Thompson, 1987). Estuarine immigration was observed from late October through April, and larvae ranged in size from 10 to 32 mm TL (Fore, 1970; Tagatz and Wilkins, 1973).

Systematic observations of larval immigration for small-scaled menhadens are unavailable. Since some spawning presumably occurs near or in some estuarine areas, oceanic larval transport may not be as critical a life-history event for these species as it is for the large-scaled species.

Juveniles

When menhaden larvae undergo metamorphosis to the juvenile stage, they have all the characteristics of an adult except for sexual maturity (Fig. 7). During transformation (prejuvenile stage), they undergo a substantial increase in relative body depth and weight, while achieving only a slight increase in length. The pronounced difference in relative body proportions is shown graphically for Atlantic menhaden by Lewis et al. (1972), and for Gulf menhaden by Deegan (1986). Length during the prejuvenile period varies between individuals and species, but is between 30 and 40 mm TL for Atlantic menhaden (Lewis et al., 1972; June and Carlson, 1971). Gulf menhaden metamorphose at a slightly smaller size, with complete transformation by 28-30 mm SL (Suttkus, 1956). An even smaller size was reported for yellowfin menhaden (laboratory-reared) by Houde and Swanson

(1975), with the transformation complete between 20 and 23 mm SL. Gunter (1945) observed post-larval finescale menhaden as small as 21 mm TL.

In addition to the more apparent external changes in body shape, significant internal morphological changes occur during metamorphosis as well. Gill rakers increase in number, length, and overall complexity (June and Carlson, 1971). The functional morphology of the resulting elaborate branchial basket is described by Friedland (1985). Intestine length increases dramatically, and a gizzard-like pyloric stomach and pyloric caeca develop (June and Carlson, 1971). These changes are diagnostic and necessary for a lifetime trophic habit of filter-feeding, microphagous planktivory.

Ultimate juvenile size achieved during estuarine residence is a function of favorable growth conditions and absolute age of individual fish. The observed size range of juvenile Atlantic menhaden is quite large (Table 3), and is attributed to the broad geographic and temporal spawning range. Most of a new year class is 10-18 months old on their first designated birthday (by convention, March 1). Hence, some individuals in a year class may be 8 months older than other individuals.

The spawning which initiates a year class begins off the New England coast in September, then proceeds southward to the U.S. Mid-Atlantic and Chesapeake Bay coasts in October and November and subsequently to the oceanic waters off the Carolinas. Spawning resumes as fish move north in early spring and continues into summer. The longest temporal period between spawning origins of a developing year class occurs in the most northern waters and the least in the more southern. Hypothetically, this type of spawning pattern should result in bimodal length-frequency distributions in geographic regions with a detectable hiatus in spawning due to migration, and a single mode in the more southerly reaches of the migratory route. Some supporting evidence for these hypotheses exists. A seasonal bimodality in length frequencies has been observed for young-of-the-year in the Chesapeake Bay area, presumably one mode resulting from spawning during the southern migration and one from spawning during the northern migration (McHugh et al., 1959). Also, preliminary length-frequency analyses of juveniles sampled in South Carolina waters indicate a fair degree of unimodality from that area, presumably from a relatively unbroken spawning period.

Table 3.—Reported ranges in length of juvenile menhaden near the end of estuarine nursery habitation. Numbers in parentheses are approximate conversions from total length to fork length using parameters from Jorgenson and Miller (1968).

Species	Range of FL in mm	Month sampled	Source
B. tyrannus	38-171	September	Kroger et al. (1974)
B. patronus	38-110	October	Unpublished[1]
B. patronus	(78-103)	August	Tagatz and Wilkins (1973)
B. smithi	63-88	August	Unpublished[2]
B. gunteri	(74-94)	"1-year-old"	Gunter (1945)

[1] Range from tagging records over several years; NMFS, SEFC Beaufort Laboratory, Beaufort, N.C.
[2] Range from tagging records, Turnbull Creek, Fla., 1971; NMFS, SEFC Beaufort Laboratory, Beaufort, N.C.

Table 4.—Maximum sizes reported for adult menhaden by species. Values in parentheses are approximate conversions from values reported, for purposes of comparison. Conversions to fork length (FL) used equations from Jorgenson and Miller (1968), while total length (TL) to standard length (SL) and vice versa used combined ratios (two large-scale species' values combined, and two small-scale species' values combined) from ranges in study specimens reported by Hildebrand (1963).

Species	TL mm	FL mm	SL mm	Source
B. tyrannus	500	(419)	(409)	Hildebrand (1963)
B. patronus[1]	265	(223)	(214)	Hildebrand (1963)
B. smithi[1,2]	(341)	(281)	257	Christmas and Gunter (1960)
B. gunteri[3]	(351)	(289)	264	Christmas and Gunter (1960)

[1] Some larger individuals of *B. patronus* and *B. smithi* were reported by Dahlberg (1970). It appears, however, that some of his reported standard lengths may be fork lengths.
[2] Fish on Figure 3 is larger than from this earlier report.
[3] Fish on Figure 4 is larger than from this earlier report.

Some juvenile length-frequency distributions from northern coastal estuaries of North Carolina appear to have two, and in some cases three, modes. The first of these modes may be attributable to spawning in October or early November by sexually maturing age-2 and some age-3 fish which summered in North Carolina or Virginia waters (Wilkins and Lewis, 1971). The second (and major) mode probably represents progeny from subsequent winter spawning by migratory adults which summered in the U.S. Mid-Atlantic and New England waters. Trimodality in length frequency distributions is sometimes observed and could result from a large portion of the migratory spawners moving even farther south, or from a cessation in spawning by the overwintering fish, or from differential survival of larvae or juveniles in winter.

A substantial variance in mean size of older juveniles exists among years. This can be partly due to density-dependent growth, as size-at-age data was shown to be inversely related to year class size, at least as early as the estuarine growth phase (Reish et al., 1985; Ahrenholz et al., 1989).

A relatively wide range in juvenile size has also been observed for Gulf menhaden (Table 3). Some of the broad range in sizes is expected as a result of their protracted spawning season. There is additional evidence for bimodality in the juvenile population, and hence suggestions of two spawning peaks (Tagatz and Wilkins, 1973). The bulk of a year class is 10-14 months old on their first designated birthday (by convention January 1). Density-dependent growth during the juvenile stage is not prominant, if present at all, and Nelson and Ahrenholz (1986) could find no evidence of density-dependent growth from an examination of fishery landings size-at-age data. However, Guillory and Bejarano (1980) reported evidence for density-dependent growth among mean lengths of juveniles sampled from several estuarine areas and subsequent catch-per-unit-effort (CPUE) data for age-1 fish in the purse-seine reduction fishery.

Much narrower ranges in size were noted for juvenile finescale and yellowfin menhaden (Table 3). This may be due to sampling limitations, as well as from a relatively less protracted spawning season.

Age and Growth of Adults

Relative to absolute size, Atlantic menhaden are the largest of the genus, Gulf menhaden are the smallest, with both small-scaled species being of intermediate size (Table 4). Similarly, the Atlantic menhaden is probably the most long lived (10-12 years) and the Gulf menhaden the shortest (5-6 years). The longevity of the small-scaled menhadens is unknown, but probably is equal to or greater than that for Gulf menhaden, and certainly less than that for Atlantic menhaden.

Size-at-age data, and hence rates of growth in years are only available for large-scaled menhadens. The technique for ageing Atlantic menhaden with scales was developed by June and Roithmayr (1960). Additional validation of the technique was provided by Kroger et al. (1974). Gulf menhaden are aged with scales by criteria developed by Nicholson and Schaaf (1978).

Since the density-dependent growth effect persists for several years in the fishery dependent size-at-age data for the Atlantic menhaden, descriptive growth equations were estimated for each year class (Ahrenholz et al., 1987b). Comparative growth curves for length and weight are given for a relatively large year class (1975) and a small year class (1970) in Figure 8. Only one equation was used to describe adult growth in Gulf menhaden in a stock assessment and population simulation study by Nelson and Ahrenholz (1986) (Fig. 9).

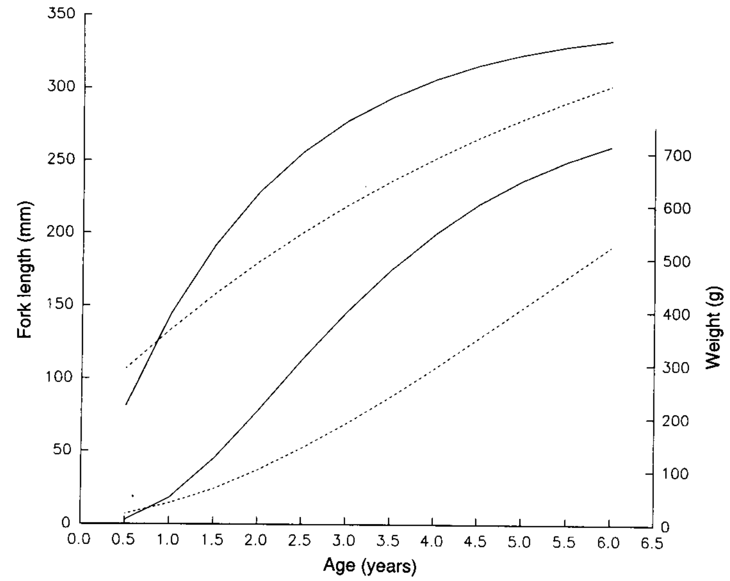

Figure 8.—Comparative fitted von Bertalanffy curves of two dissimilar sized Atlantic menhaden year classes (numbers of fish), 1970 (small year class, solid curves), and 1975 (large year class, dashed curves). Upper curves are fork lengths in millimeters, lower curves are weights in grams, as a function of age in years.

Trophic Relationships

Because the general morphology of menhaden is similar, a high degree of similarity among species with respect to their roles as both predators and prey is assumed. Observations and study results are given here by the particular species upon which they were made, but, in general, parallel conclusions should be possible for the other menhaden species.

Menhaden As Consumers

From the first-feeding larval stage into the prejuvenile stage, Atlantic menhaden selectively sight-feed on individual planktonic organisms (Chipman, 1959; June and Carlson, 1971). Govoni et al. (1983) noted that small Gulf menhaden larvae feed heavily on larger phytoplankton (predominantly dinoflagellates) and some zooplankton. As the larvae grow, phytoplankton become less important in the diet, and (larger) zooplankton, especially copepods (all life stages) become more important. After metamorphosis, filter feeding omnivory becomes the rule. Juveniles consume zooplankton and phytoplankton, but interestingly, some of the phytoplankton they consume are an order of magnitude smaller than the smallest phytoplankton consumed during the larval phase (Chipman, 1959; June and Carlson, 1971). Darnell (1958) found relatively large quantities of phytoplankton along with detritus and some zooplankton in the guts of small juvenile Gulf menhaden.

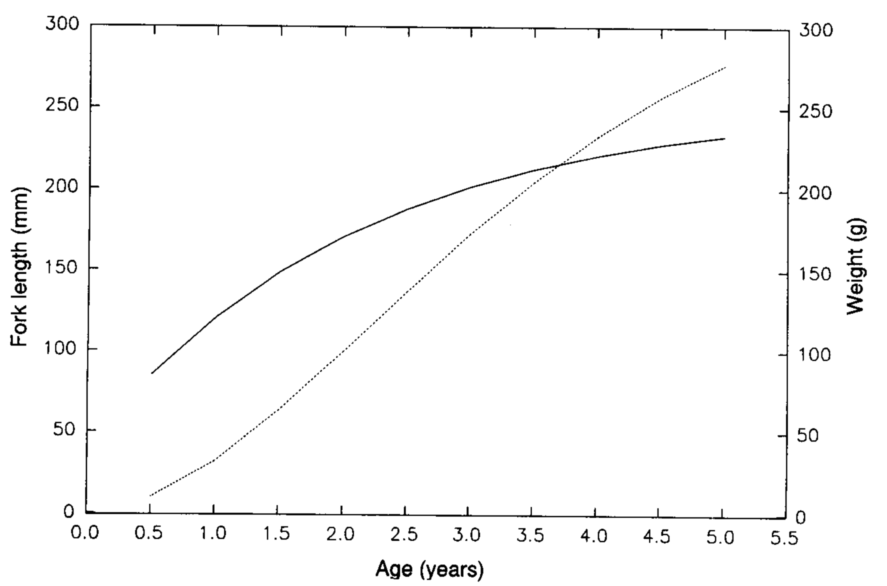

Figure 9.—Fitted von Bertalanffy curves of mean size-at-age for Gulf menhaden, solid curve is fork length in millimeters, dashed curve is weight in grams.

Adult Atlantic menhaden stomach contents examined by Peck (1893) consisted of phytoplankton (especially dinoflagellates and diatoms); zooplankton; greenish, brownish, or yellowish organic "mud" or amorphous matter; and detritus. He also examined stomach contents from juveniles and found the same type of organic material that was in adult fish. Because of the menhaden's elaborate, highly specialized gill-rakers for filter-feeding, Peck (1893) hypothesized that what was in the surface waters could also be found in menhaden stomachs. He further demonstrated this conclusion by pouring sampled seawater through a gauze and white sand filter. This paper emphasized that similarities and differences in the composition of the fishes' diet are due to local variations.

Peck's (1893) hypothesis has been only slightly modified by more recent studies. The relative composition of micro-organisms/materials within the fishes' stomachs, as compared to that in the surrounding water, is a function of the menhaden's filtering efficiencies for different sizes and types of organisms. In addition, there is some minimum size threshold, below which the fish is incapable of capturing by filtration, as well as a maximum size, above which the fish will simply avoid (and/or the organism avoids the fish). A knowledge of these maximum and (especially) minimum thresholds is critical for the determination of the ecological role of Atlantic menhaden (Durbin and Durbin, 1975; Friedland et al., 1984). Of major concern is the nanoplankton (2-20 μm by classification of Sieburth et al., 1978), which can be a dominant fraction of the phytoplankton production in estuarine and nearshore systems, especially during summer (see Durbin et al., 1975; McCarthy et al., 1974).

The minimum size threshold for adult menhaden (about 260 mm FL) was determined from feeding experiments to be 13-16 μm (Durbin and Durbin, 1975). Friedland et al. (1984) determined the minimum size threshold for juveniles (about 138 mm FL) to be 7-9 μm. They noted an increase in filtering efficiency for some types of organisms when detritus was present in the water column. Since the minimum threshold appears to be a function of fish size, the abundant 40-90 mm FL juveniles present in estuarine systems during spring and summer, probably take advantage of the predominating primary productivity occurring within the nanoplankton segment of the plankton community.

On the other extreme, Friedland et al. (1984) noted maximum filtration efficiency occurred for objects about 100 μm in diameter for the 138 mm FL juveniles, but did not give an estimate for maximum acceptable prey size. Durbin and Durbin (1975) did not give a prey size for maximum filtration efficiency, but they did note that the maximum acceptable prey size was between 1,200 μm and 10 mm, as prey (copepods) of the smaller size were consumed while those of the larger (adult brine shrimp) were not.

In addition to the living organisms consumed, varying quantities of detritus and/or amorphous material is also injested while filter feeding. While the actual organic source of this material, and the actual magnitude of the energetic contribution it makes, can vary by habitat type and is not well known, evidence of the digestion and subsequent absorption of this material by menhaden is accumulating (Jeffries, 1975; Lewis and Peters, 1984; Peters and Lewis, 1984; Deegan et al., 1990).

Menhaden As Forage

All life history stages of menhaden from egg through adults are potential prey for a large variety of predators. Moreover, the potential exists for menhaden to feed on their own eggs (Nelson et al., 1977), as well as the eggs and larvae of other fishes and invertebrates (Peck, 1893; McHugh, 1967). Larvae and juveniles of a number of piscivorous species of fish potentially prey upon menhaden larvae, depending on their coincidence in space and time, along with compatible body sizes. Many invertebrate predators, especially in oceanic waters, can be expected to prey upon menhaden larvae; notable among this group are the abundant chaetognaths (Clements, 1990). Other potential invertebrate predators include, but are not limited to, squids (mollusks) and ctenophores and jellyfishes (coelenterates).

In estuarine and marine waters of the U.S. Atlantic and Gulf coasts, menhaden juveniles and adults are potential prey for a large number of species and sizes of piscivorous fishes (Sykes and Manooch, 1979). The relative degree of predation will again be a product of the coincidence in space and time of the potential predators and prey, and their relative sizes. For the most part, prey selection among menhaden predators appears to be predominantly opportunistic. However, since menhaden are so widespread and abundant in estuarine and nearshore systems, they are frequently an important component of many fishes' diets during one or more time periods within the year. For example, Atlantic menhaden were reported as an important component of the diet of striped bass, *Morone saxatilis*, in Albemarle Sound, N.C. (Manooch, 1973), but of variable importance to weakfish, *Cynoscion regalis* (Merriner, 1975). Peck (1893) noted that bluefish, *Pomatomus saltatrix*, and bonito, *Sarda sarda*, are major predators of menhaden, and pointed out that the potential breadth of the role of Atlantic menhaden as prey is well demonstrated by its popularity as bait.

Menhaden are thought to be an important forage for piscivorous birds, e.g. brown pelicans, *Pelecanus occidentalis*, and are known to be heavily preyed upon by osprey, *Pandion haliaetus* (Spitzer, 1989) and common loons, *Gavia immer* (Spitzer[1]). Menhaden were also reported as prey for marine mammals (Hildebrand, 1963).

Parasites and Disease

Two common parasites encountered on Atlantic menhaden are the parasitic isopod, *Olencira praegustator*, and the parasitic copepod, *Lernaeenicus radiatus*. The relatively common occurrence of *O. praegustator* in the mouth and throat of *B. tyrannus* is reflected by one of the Atlantic menhaden's early common names, i.e., "bug-fish" (Smith, 1907). Kroger and Guthrie (1972a) noted that the highest rate of infestation of this isopod among juvenile Atlantic

[1] P. R. Spitzer, Univ. Md. System, Cent. Environ. Est. Stud., Horn Point Environ. Lab., P.O. Box 775, Cambridge, MD 21613. Personal commun.

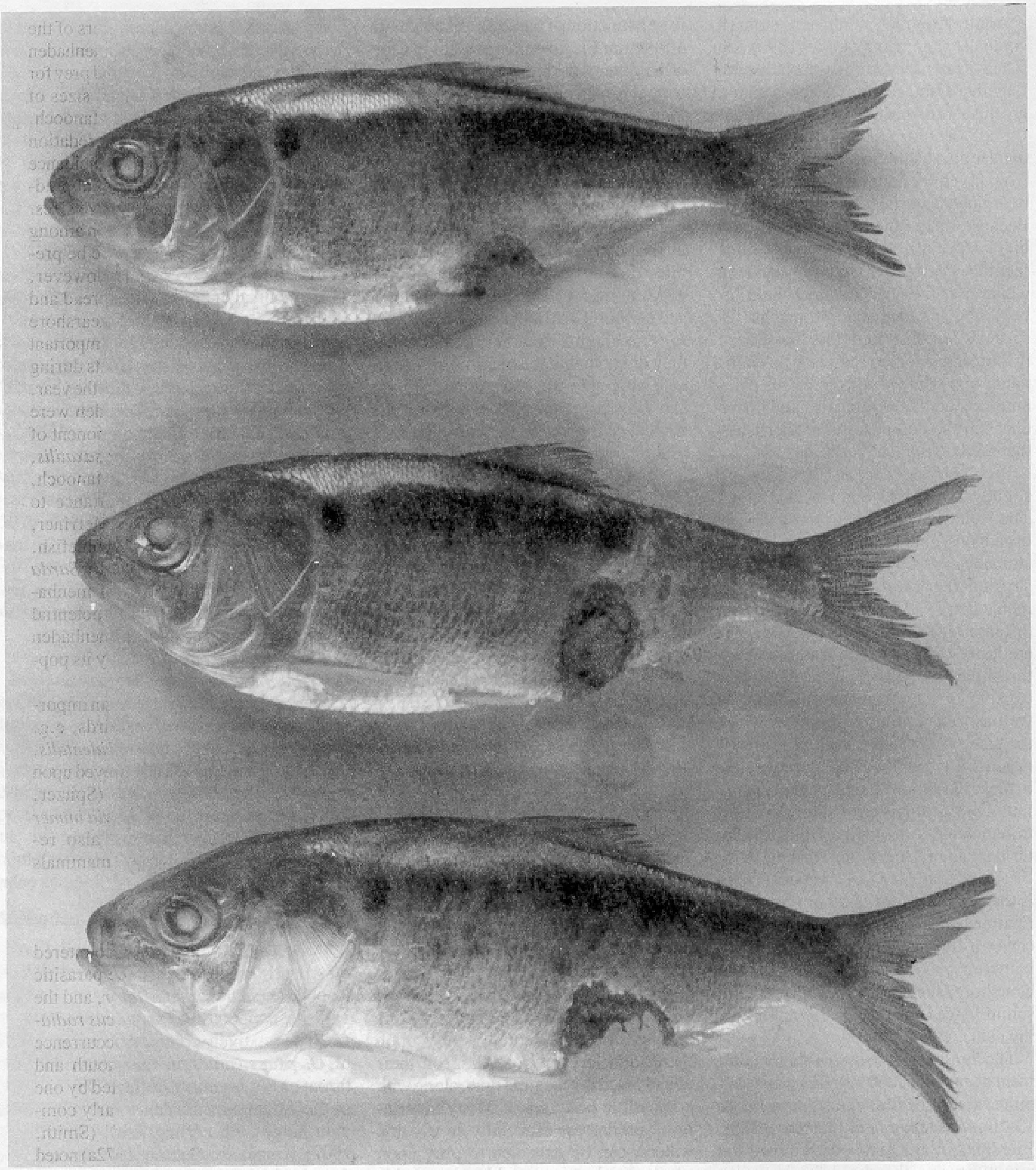

Figure 10.—Ulcerative mycosis lesions on juvenile Atlantic menhaden from Hancock Creek, N.C. (fall of 1986).

menhaden was in estuaries along the mid-portion of the fishes' range, i.e., Virginia through New Jersey.

In addition to Atlantic menhaden, *O. praegustator* has been reported in specimens from the Atlantic and Gulf populations of yellowfin menhaden, as well as Gulf menhaden, and both the hybrids *B. patronus* × *B. smithi* and *B. tyrannus* × *B. smithi* (Dahlberg, 1969; Turner and Roe, 1967). Similarly, the copepod *L. radiatus* has been found on the large-scaled species of menhaden and their hybrids with *B. smithi*, as well as *B. smithi* from the Gulf of Mexico and Atlantic populations (Dahlberg, 1969). Lists of additional parasites of Atlantic menhaden are contained in Westman and Nigrelli (1955), Hildebrand (1963), and Reintjes (1969).

Two major diseases are commonly associated with Atlantic menhaden. Westman and Nigrelli (1955) reported on annual die-offs in the New York area. The dying fish, "spinners" (hence "spinning disease") were characterized as having lost coordinated movements, with one or both eyes protruded, and with hemorrhages in the gills, eyes, and optic lobes of the brain. Similar mortalities have been noted among Atlantic menhaden in Chesapeake Bay (Reintjes, 1969). The cause of these mortalities was undetermined. A virus has subsequently been identified as the agent of this disease, at least in Chesapeake Bay (Stephens et al., 1980).

The second disease, ulcerative mycosis (UM), became prominent in recent years. Atlantic menhaden with deep, crater-like lesions of UM, were observed in collections from the Pamlico River, N.C., during spring 1984 by personnel from the North Carolina Division of Marine Fisheries. Although these lesions occurred on most areas of the body, they were most common in the anal area (Noga et al., 1988) (Fig. 10). Hargis (1985) provided an early description of this disease. Pathological investigations of infected fish revealed the presence of aseptate fungal hyphae of the genera *Aphanomyces* and *Saprolegnia* in the area of the lesions (Dykstra et al., 1986; Noga and Dykstra, 1986). During 1985, Ahrenholz et al. (1987a) found infected juvenile Atlantic menhaden from estuarine systems from Delaware Bay to northern Florida. They suggested that the infected fish captured in South Carolina and Georgia were actually migrants from an area of primary infection farther north. This report also noted fish which had lesions that resembled UM from collections made in New York estuaries in 1982.

Although UM has been detected in various families of estuarine dependent fishes (Sindermann, 1988), it has not been reported from the other three species of North American menhadens. However, Noga et al. (1988) pointed out that what was reported by Kroger and Guthrie (1972b) as wounds attributed to predators on some juvenile Gulf menhaden as caused by predators, appeared similar to UM lesions.

Population Processes

Stock Structure

Considerable debate relative to the stock structure of the Atlantic menhaden population has been expended, and as many as three different stocks have been advanced, primarily on the basis of meristic and morphometric analyses (June, 1958, 1965; Sutherland, 1963; June and Nicholson, 1964; Nicholson, 1972, 1978; Dryfoos et al., 1973; Epperly, 1989). Some evidence for the presence of more than one stock exists; however, the fish reared in different geographic areas and those from different temporal spawning cohorts appear to mix rapidly due to the nature of their movement patterns. Since potentially different spawning groups are currently inseparable in the Atlantic purse-seine reduction fishery, the Atlantic menhaden population is treated as a single exploited stock with respect to that fishery.

In marked contrast to Atlantic menhaden, Gulf menhaden lack any systematic seasonal movement through their range and tend to mix very slowly. Tagging studies revealed that movement across the Mississippi Delta is infrequent, either within or between seasons (Kroger and Pristas, 1975; Pristas et al., 1976). Hence, it has been suggested that the Gulf menhaden population could be treated as two management stocks, even though differences in meristic characteristics (hence potential genetic separation) are insignificant between eastern and western populations (GSMFC, 1988). However, population dynamics analysts treat the Gulf menhaden population as a single biological and managerial stock relative to the purse-seine reduction fishery (Nelson and Ahrenholz, 1986; Vaughan, 1987; GSMFC, 1988).

On the east coast of Florida, the yellowfin menhaden, the extreme southern portion of the Atlantic menhaden population, and their hybrids appear to comprise the "stock" for a menhaden bait fishery. Similarly, on the west coast of Florida, the yellowfin menhaden, the southeastern most portion of the Gulf menhaden population, and their hybrids represent the "stock" for another menhaden bait fishery. Yellowfin menhaden from each coast of Florida are probably genetically separate populations. Dahlberg (1970) gives some meristic comparisons for these potentially distinct populations. Very little is known or speculated relative to genetic mixing within the population of finescale menhaden.

Mortality

Traditionally, losses in numbers of individuals from fish populations (total mortality) are ascribed to either fishing or natural mortality. Analytical procedures used to estimate instantaneous rates of total (Z) and fishing (F) mortality for each of the large-scaled menhaden populations assume constant rates of instantaneous natural mortality (M) among time intervals and estimated rates of fishing for each interval (Nelson and Ahrenholz, 1986; Ahrenholz et al., 1987b; Vaughan, 1987; Vaughan and Smith, 1988). The catch-at-age data does not contain enough information to estimate both M and F simultaneously, as they are additive exponential rates ($Z = F + M$). Thus, the computational procedures have ascribed to F all the variances observed in Z among time intervals, even though true M also probably varied as well, albeit to a lesser degree.

The estimate of M recently used in assessment analyses for Atlantic menhaden is $M = 0.45$. This estimate is a mean of a range of available estimates: Dryfoos et al. (1973) estimated $M = 0.52$

from an analysis of returns of adult-tagged Atlantic menhaden; Reish et al. (1985) estimated $M = 0.50$ for ages 2 and 3 from analyses of tag returns of both adult- and juvenile-tagged fish; Schaaf and Huntsman (1972) estimated $M = 0.37$ from an analysis of catch statistics.

An estimate of $M = 1.1$ has been used in stock assessment analyses for Gulf menhaden (Nelson and Ahrenholz, 1986; Vaughan, 1987; GSMFC, 1988); it represents the mean of six estimates of M ranging from 0.69 to 1.61, obtained from an analysis of mark-recovery data (Ahrenholz, 1981).

Since estimates of M for both Atlantic and Gulf menhaden were obtained from purse-seine reduction landings or tag recoveries from reduction plants, they include "other" losses. In addition to predation and disease, losses due to bycatch in other fisheries, as well as landings for bait are included as losses in M.

No estimates for M are available for either of the two small-scaled menhadens. Values of M are probably intermediate between those for Atlantic and Gulf menhaden.

Recruitment

Tempered by the number of age classes represented in the fisheries, fluctuations in year-class size have naturally contributed to the variability in landings among years (Smith, 1991). Estimates of recruitment into the Gulf menhaden stock at age 1 have varied more than fivefold, while estimates of recruitment into the Atlantic stock at a similar age have fluctuated almost thirteenfold (Vaughan and Merriner, 1991).

The observed uncertainty for menhaden recruitment among years and its ramification for landings have fostered a number of different investigations ranging from those designed to determine if fishing was impacting recruitment to those designed to predict recruitment and/or landings. Additionally, studies were designed to directly sample and estimate prerecruitment abundance.

Factors affecting recruitment are traditionally categorized as density dependent, where the absolute spawning stock size and the size of the subsequent year class are related; or density independent, where the number of recruits to the population are dependent on one or more environmental factors. Removal of adult fish from the population can have a pronounced effect on subsequent recruitment if the stock-recruitment relationship is strong. Results from analyses conducted by Schaaf and Huntsman (1972) revealed a very weak association between the spawning stock size and subsequent recruitment for Atlantic menhaden. Later analyses used potential egg production in place of spawning stock, but did not substantially improve the analytical relationship (Nelson et al., 1977). The data used in both analyses, when plotted as scatter diagrams, did not display any pattern well enough to suggest an appropriate functional model. Of the two theoretical recruitment functions commonly used, Ricker's (1954) equation, which results in a dome-shaped curve, was selected on biological grounds for both of the earlier reports (Schaaf and Huntsman, 1972; Nelson et al., 1977). For example, menhaden may consume their own eggs under certain circumstances, which can contribute to the descending right hand limb of the Ricker curve. Further, four other ocean-spawning clupeids are thought to be represented by a dome-shaped curve (Cushing, 1971). Based on statistical grounds, Reish et al. (1985) preferred the function developed by Beverton and Holt (1957) for simulation purposes.

Nelson and Ahrenholz (1986) found that potential egg production-recruitment scatter plots for Gulf menhaden were dome-shaped. Coupled with biological arguments, they used the Ricker function for both description and subsequent population simulation studies.

Since deterministic, density-dependent spawner-recruitment functions alone would be of little value in predicting subsequent year-class sizes of Atlantic menhaden, Nelson et al. (1977) developed a mixed regulatory factor (both density-dependent and density-independent) model. First, they fitted a density-dependent Ricker function to the potential egg production-recruitment data, then used the deviations from the fitted model to develop a survival index. This index was in turn the dependent variable for a multiple regression analysis with environmental variables which were considered important a priori. Emphasis was placed on Ekman transport, which was thought to be a substantial contributor to oceanic currents which would bring larval Atlantic menhaden from offshore spawning areas to the vicinity of inlets and estuarine nursery areas. The resultant model described the recruitment data for 1955-70 fairly well. Though conceptually sound, this model did not effectively describe the recruitment estimates obtained during the 1970's and early 1980's. Reish et al. (1985) felt that much of the strong statistical correlation obtained by Nelson et al. (1977) for Ekman transport was due to one data point, i.e., the exceptionally large 1958 year class. Additional mixed regulatory factor models were developed by Yoshiyama et al. (1981), who preferred a Ricker function with an environmental parameter (Ekman transport at lat. 35°N., long. 75°W.) in the stock-independent term of the equation.

Checkley et al. (1988) described a process-oriented study relative to spawning, larval transport, and early survival of Atlantic menhaden. They suggested that spawning off the North Carolina coast occurred along the western wall of the Gulf Stream, and that the ultimate survival of larvae was dependent on storm-induced upwelling and buoyancy-driven transport (the result of water and air temperature differentials). They also postulated that events on the order of days rather than months, were critical to spawning and larval transport and development.

Shaw et al. (1985b, 1988) examined onshore transport and subsequent estuarine immigration processes for Gulf menhaden larvae. They hypothesized that larvae spawned in the waters west of the Mississippi Delta moved shoreward in a west-northwesterly direction and subsequently enter more westerly estuaries, rather than estuaries nearer to where spawning actually occurred. These studies may ultimately permit a more refined examination of potential environmental factor influences on larval survival over a reduced temporal and geographic scale.

Two studies which emphasized environmental variables and are at least tangentially related to fishery recruitment, were conducted on Gulf menhaden. In the first study, Stone (1976) conducted an extensive, systematic, multiple-regression search of various environmental data. Methodical temporal lags and commercial fishing effort were used as independent variables to detect any potential relationships between these variables and landings of Gulf menhaden. Some of the analyses were conducted using monthly time periods. He thought that environmental factors which influence important life history events (especially factors affecting recruitment) could be detected by the analyses when appropriately temporally matched.

The second study was reported by Guillory et al. (1983), who used first-order linear regressions and stepwise multiple regressions to determine the relationship between a wide variety of environmental factors, both singly and in combination. They examined catch-per-sampling-effort (CPSE) of young-of-the-year Gulf menhaden from otter trawl shrimp abundance surveys in Louisiana estuaries (Guillory and Bejarano, 1980), as well as landings of age-1 Gulf menhaden per-vessel-ton-week of effort (CPUE as reported earlier) by the commercial purse-seine fleet from Louisiana ports. Both the CPSE and CPUE values were used as surrogates for recruitment estimates (year-class strength).

In general terms, Guillory et al. (1983) and Stone (1976) found some strong correlations for the temporally lagged variables such as temperature (air or water), and wind speed and direction, with the CPUE and CPSE values and landings, respectively. Stone's (1976) analyses provide some insight into important environmental variables, but only at a more general level. Recruitment variability is not clearly expressed in purse-seine landings because they are dominated by two age classes. But, predictions of landings, not year-class sizes, were apparently the desired products of Stone's (1976) analyses. In addition, the author stated that potential environmental effects could be masked in the regression models by effort and temporal effects. Finally, the results have to be viewed cautiously because systematic, exploratory regression analyses have a high probability of providing some spurious relationships.

Guillory et al. (1983) treated each year class separately, thus, their models may provide some insight into important environmental factors. As with Stone's (1976) work, however, caution must be exercised in applying the results because there is a strong possibility of spurious correlations resulting from such a large number of exploratory regressions. This is especially true when using the CPSE values, as they are the result of an earlier exploratory series of analyses (Guillory and Bejarano, 1980). Additionally, the predictive accuracy of relationships will depend on how strongly CPUE of age-1 menhaden reflects true year class size.

The NMFS Beaufort Laboratory attempted to obtain prerecruitment estimates of year-class strength by directly sampling juvenile menhaden in estuarine areas a few months prior to their emigration and recruitment into the coastal populations. Some forms of juvenile relative abundance sampling began as early as 1956 on the Atlantic coast (Ahrenholz et al., 1989). Two-boat, surface-trawl surveys were initiated for juvenile Atlantic menhaden in 1962 and for juvenile Gulf menhaden during 1964 (Turner, 1973; Turner et al., 1974). The studies culminated with an extensive two-boat, surface-trawl relative abundance survey on each coast from the early 1970's through 1978. Although density estimates from these surveys appeared to reflect local and regional abundance of menhaden, they did not correlate well with subsequent virtual population analyses estimates of year-class size for either coast (Ahrenholz et al., 1989). Nevertheless, these surveys were invaluable for determining juvenile menhaden distribution patterns in estuaries and aided many life history studies, even though they had limited predictive application.

The limited success of attempts to model or estimate recruitment at relatively young ages may well be due to oversimplification in the models' or sampling programs' designs relative to the complexity of the recruitment patterns. With respect to at least Atlantic menhaden, an accounting must be made of both the geographic and temporal spawning origins of prerecruits. Research along these lines is being conducted.

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Overview of Mark-recovery Studies on Adult and Juvenile Atlantic Menhaden, *Brevoortia tyrannus*, and Gulf Menhaden, *B. patronus*

DEAN W. AHRENHOLZ, DONNIE L. DUDLEY, and ELDON J. LEVI

ABSTRACT—Extensive mark-recapture studies using internal ferromagnetic tags have been conducted on Atlantic menhaden, Brevoortia tyrannus, *and Gulf menhaden,* B. patronus. *From 1966 through 1969, 1,066,357 adult Atlantic menhaden were tagged; subsequently, from 1970 through 1987, 428,272 juveniles of this species were tagged. Similarly, from 1969 through 1971, 75,673 adult Gulf menhaden were tagged; concurrently from 1970 through 1985, 236,936 juveniles were tagged and released. This report provides an overview of the history of the tagging program, methodologies for both release and recovery activities, a summary of release areas and number of fish tagged within each area, and a review of assumptions necessary for the analysis of this type of mark-recovery data. The resulting data sets have proven to be highly useful for a variety of analyses ranging from determination of migratory patterns and population structure to estimating mortality rates. The relatively wide range of acceptance of tagging results by laymen, industry, and analysts alike have made these data extremely useful for management-oriented analyses.*

Introduction

Mark-recapture programs conducted by the Beaufort Laboratory of the NMFS Southeast Fisheries Science Center have played an important role in the determination of migratory habits, stock structure, and the estimation of mortality rates for Atlantic menhaden, *Brevoortia tyrannus*, and Gulf menhaden, *B. patronus*. Adult Atlantic menhaden were marked and released on the fishing grounds from 1966 through 1969 (Dryfoos et al., 1973), while adult Gulf menhaden were tagged and released from 1969 through 1971 (Pristas et al., 1976). Large numbers of juvenile (young-of-the-year) menhaden were captured, marked, and released in U.S. coastal estuaries on the Gulf of Mexico coast (Kroger and Pristas, 1975; Ahrenholz, 1981) and on the Atlantic coast (Kroger and Guthrie, 1973), with emphasis placed on determining recruitment patterns of menhaden on the basis of estuarine origin.

Internal, ferromagnetic, stainless steel tags were successfully used to tag both adult and juvenile menhaden. Mark-recapture studies using external marks requiring visual detection are considered impractical because commercial landings by an individual menhaden purse-seine vessel may range from 100,000 to 2,000,000 fish which are loaded and unloaded by fish pumps. Moreover, at least 95% of the menhaden landings on both the Atlantic and Gulf coasts are for reduction to fish meal, and estimates of numbers of fish landed range into the billions.

This paper provides an overview of the NMFS menhaden tagging program, summarizes when, where, and how many fish were released, and introduces analytical adjustments required for analysis of the internal, ferromagnetic mark-recovery data.

Brief History of the Tag

Development of an internal (body cavity) tag is credited to Robert A. Nesbit, who in 1931 internally marked weakfish, *Cynoscion regalis*, with a thin strip of colored celluloid (Rounsefell and Everhardt, 1966). In 1932, Rounsefell and Dahlgren (1933) developed internal magnetic tags to mark Pacific herring, *Clupea pallasii*. The early tags were pure nickel; later, nickel-plated steel was used. This modification greatly increased the recoverability of the tags on magnets (Dahlgren, 1936). In addition to herrings, these tags were also used in extensive marking programs on Pacific sardine, *Sardinops caerulea*, from 1935 through 1942 (Hart, 1943; Clark and Janssen, 1945). Experimental programs using internal tags to mark Norwegian spring spawning herring were conducted in Europe in 1948 (Dragesund and Jakobsson, 1963). Jakobsson (1970) appropriately commented regarding internal magnetic tags: "The development of this magnetic body cavity tag heralded a breakthrough in the tagging of herring and several other pelagic fish which are bulk-handled and sold for reduction in fish meal plants."

After a series of marking experiments in 1961 and 1962 which compared two sizes of nickel plated steel tags similar to those used in the Pacific sardine (Janssen and Alpin, 1945) and Pacific herring (Dahlgren, 1936) and stainless steel tags similar to those used for tagging Atlantic herring in Norway (Dragesund and Hognestad, 1960), Carlson and Reintjes (1972) concluded that the stainless steel tag was the most suitable for menhaden. Extensive testing (Carlson and Reintjes, 1972; Kroger and Dryfoos, 1972) indicated that smooth-edged stainless steel tags were preferable to rough-edged nickel-plated steel tags for menhaden. The NMFS menhaden tagging program adopted a large stainless steel tag (14.0×3.0×0.5 mm) for adult menhaden and a small stainless steel tag (7.0×2.5×0.4 mm) for juvenile menhaden (Dryfoos et al., 1973) (Fig. 1). After 1974, both large and small tags were used to tag juveniles. Each large tag is unique, identifiable with a prefixed letter and five digits. The small tags, however, are identifiable in lots of 100 with either three digits, a letter and two digits, or two letters and one digit.

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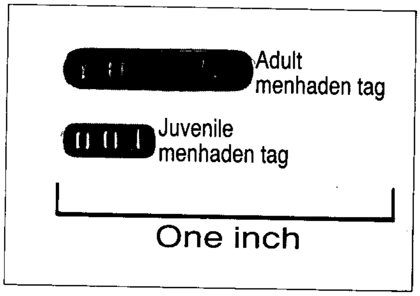

Figure 1.—Large (adult) and small (juvenile) ferromagnetic menhaden tags.

Tagging Procedures

Considerable experimentation was conducted on application methods (angle and area of injection into the body cavity), treatment of tags (antibiotics and disinfectants), and equipment used for the injection (scalpel-forceps or tagging gun). Kroger and Dryfoos (1972) concluded that a compromise between minimizing shedding and mortality was obtained by injecting the large tag through the body cavity wall in an anterior direction, at a site slightly posterior to the pelvic fin and up about one-third of the body depth (= regular method). The best results for the small tag were obtained by injecting the tag posteriorly from a site just below and behind the insertion of the pectoral fin (= pectoral method). Although subject to variation among individual taggers (Kroger et al., 1974b), the regular method has been used for tagging adult menhaden. The pectoral method was employed to tag juveniles (whether small or large tags were used), with the exception of a series of experimental releases in 1972 where tags were injected into the air bladders of juvenile Atlantic and Gulf menhaden (Kroger et al., 1974b).

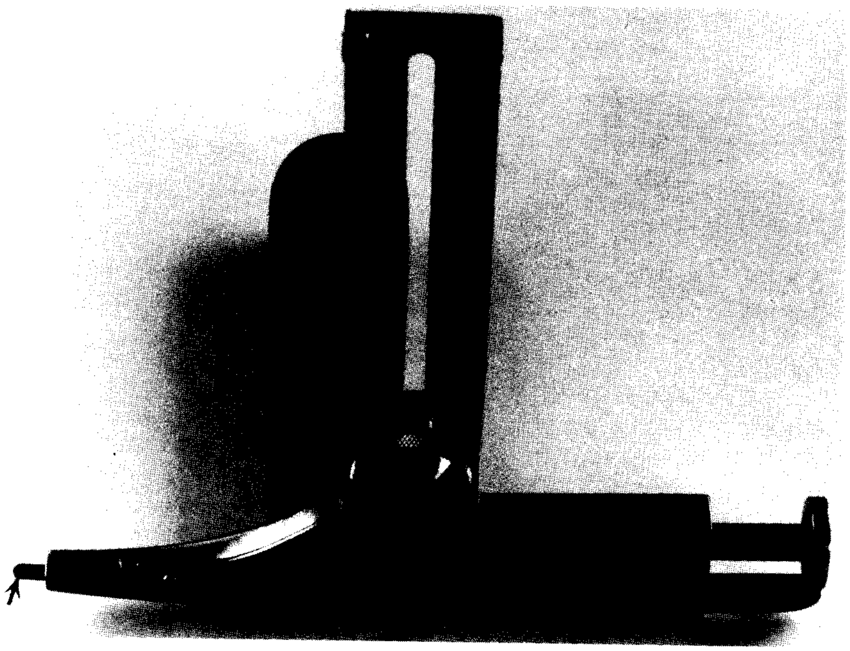

Figure 2.—Typical tagging gun used in menhaden mark-recovery studies. Note tag projecting from barrel to the left.

Figure 3.—A tag is injected into an adult menhaden.

With respect to treating tags with disinfectants and antibiotics, Kroger and Dryfoos (1972) reported that lower mortality rates of fish injected with treated tags were offset by higher shedding rates of treated tags. Hence, the use of untreated tags was recommended.

When experimentally applying tags with the scalpel-forceps method, a small incision was made with the scalpel at the appropriate anatomical site, and the tag was inserted into the body cavity with the forceps. With the tagging guns (which hold about 100 tags), the tags extend slightly beyond the tip of the gun barrel and the projecting tag itself is used to make the incision (Fig. 2). The tag is then pushed into the body cavity by both the remaining tags in the barrel and the plunger (Fig. 3). The penetration depth

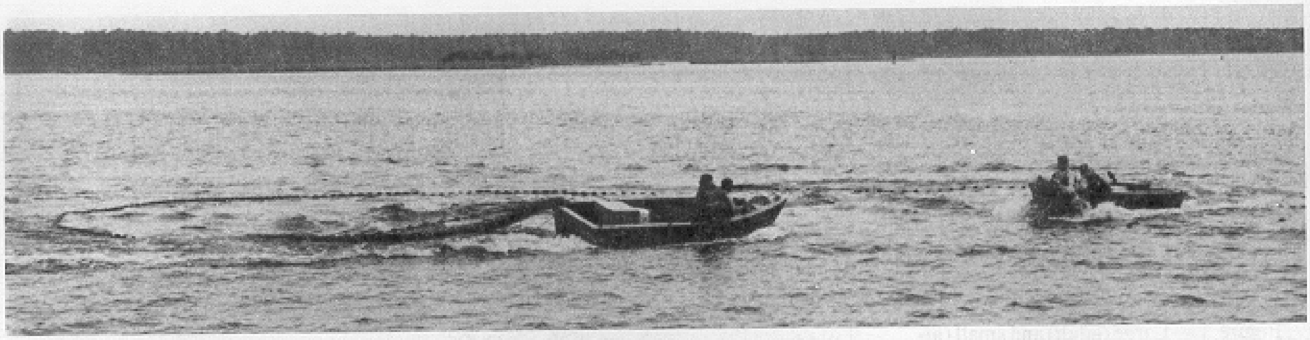

Figure 4.—NMFS purse-seine boats make a set.

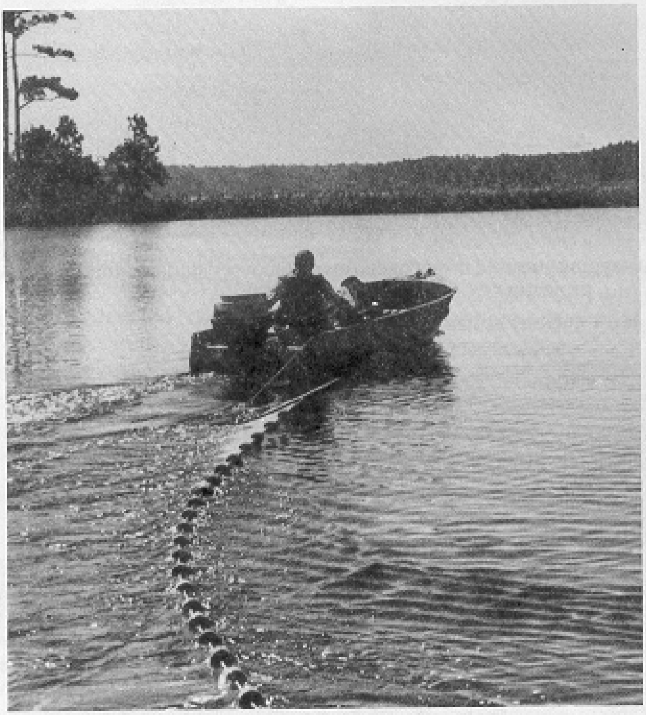

Figure 5.—Beginning a haul-seine sweep to capture juvenile menhaden.

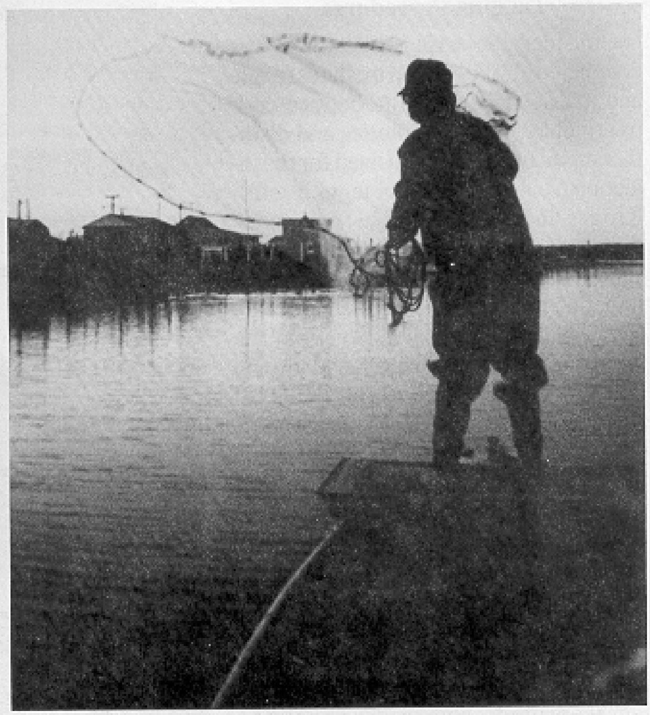

Figure 6.—Cast netting juvenile menhaden in an estuary.

is determined by the distance the tags projected from the barrel tip. The tagging guns were used because they were faster and safer than the scalpel and forceps for injecting tags. An early problem with high rates of tag shedding using the tagging guns was greatly reduced by employing guns with shorter barrels (hence greater projection of tags and deeper body penetration) (Kroger and Dryfoos, 1972).

Menhaden were obtained for field tagging by a variety of methods. Adult Atlantic menhaden were obtained from commercial purse-seine and pound-net catches, as well as off-season catches by NMFS haul seines, pound nets, and purse seines (Dryfoos et al., 1973; Pristas and Willis, 1973; Levi, 1981) (Fig. 4). Adult Gulf menhaden were obtained from commercial purse-seine catches (Pristas et al., 1976). During the earlier years of the tagging program, juvenile Atlantic menhaden were obtained by haul seining (Fig. 5), and juvenile Gulf menhaden by two-boat surface trawls (Ahrenholz et al., 1989). Since 1983, however, juveniles of both species have been captured with cast nets (Fig. 6).

Recovery Procedure

Tags that entered a menhaden reduction plant were recovered by powerful magnets installed at strategic points along the processing system. Some of the magnets had been installed earlier by the companies to remove stray pieces of metal from the fish scrap; additional magnets were provided by the NMFS and installed by plant personnel. Three types of industrial magnets were used: Plate, grate (or drawer) tubular, and rotating grate (Fig. 7). Magnets located adjacent the meal dryer and along the conveyor system to the scrap shed (primary magnets) normally recovered tags from fish within a few days of landing. Magnets located in the scrap storage shed and meal grinding area (secondary magnets) recovered tags from landings made weeks or months earlier (Fig. 8).

The magnets were cleaned at daily to several day intervals, depending on the processing activities within the plant (Fig. 9). Separation of tags from the material scraped from the magnets, a mixture of fish scrap and chunks of metal, required several steps. The collected mixture was spread over a flat surface and the metal concentrated and removed from the fish scrap with a magnetic sweeper (Fig. 10). The concentrated metal was further sorted with sieves. The reduced mixture containing the tags and minute metal particles was then sorted by hand over a contrasting background (Parker, 1973).

An electronic detector-recovery system was successfully developed and used during the summer of 1967 (Parker, 1972). This system provided for the recovery of whole tagged fish. These recoveries were used to validate annulus formation on scales for Atlantic menhaden, examine tagging wounds for rates of healing, and determine the best site on the body of the menhaden for tag incision. However, the system was too costly and time consuming for routine tag recovery operations.

Summary of Tag Releases

Initially, the goals of the tagging program focused on determining migratory habits, stock structure, and survival rates for the Atlantic menhaden population (Dryfoos et al., 1973). The U.S. Atlantic coast was divided into five tagging areas (Fig. 11). These areas were, for all practical purposes, the same (but not identical) as the currently recognized fishing areas (Ahrenholz et al., 1987), except the area south of the Virginia-North Carolina border was divided into two areas (Coston, 1971; Dryfoos et al., 1973). Tagging within each area was conducted during most of the seasonal periods when menhaden were present. From 1966 to 1969, more than 1 million

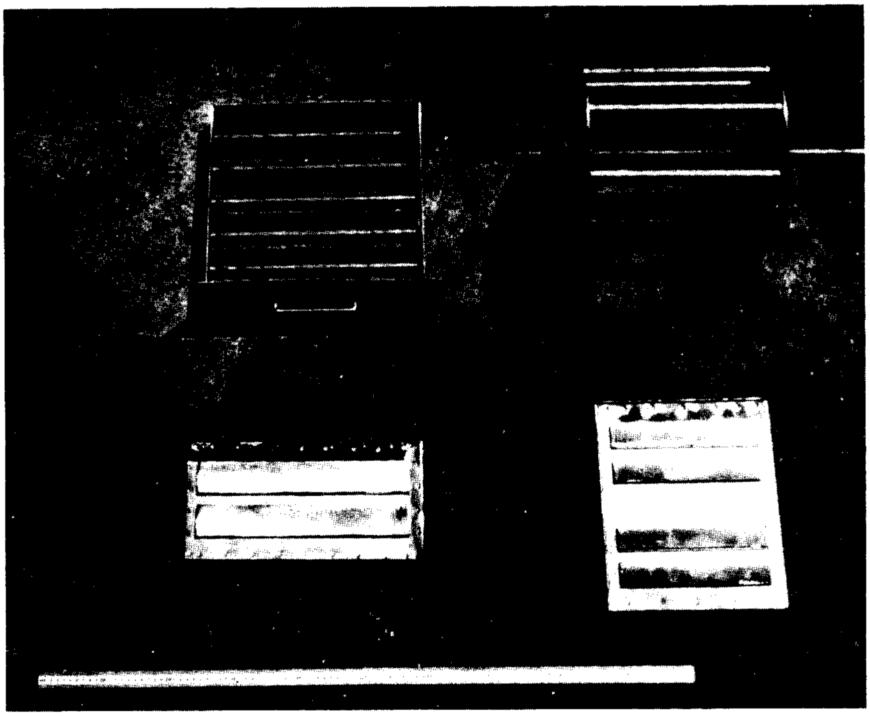

Figure 7.—Grate, rotating grate, and two kinds of plate magnets used to recover ferromagnetic fish tags from fish scrap.

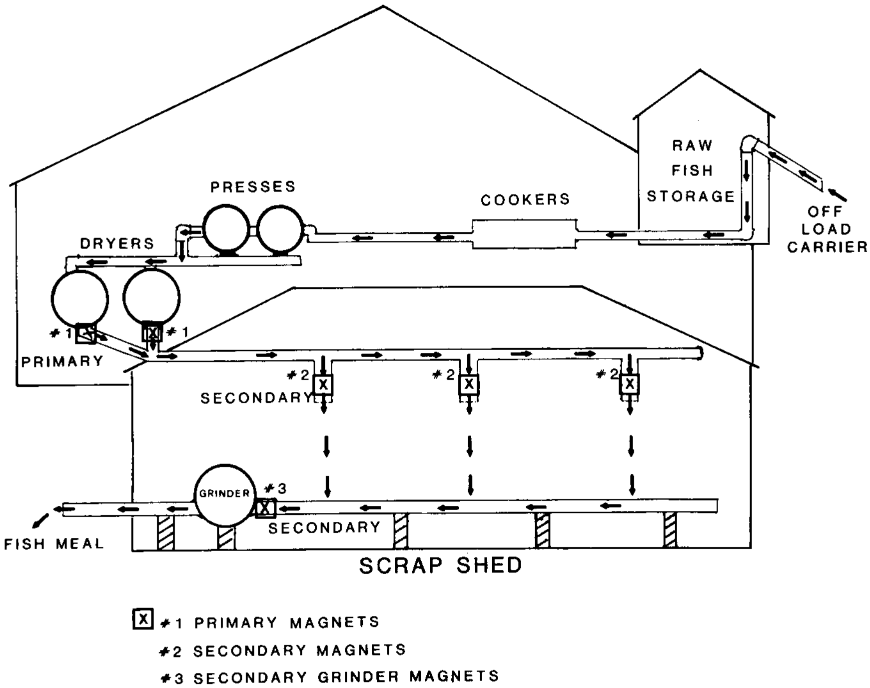

Figure 8.—Diagrammatic representation of a menhaden reduction plant showing magnet locations (x's) and type designation (see text).

Figure 9.—Plate magnet being cleaned.

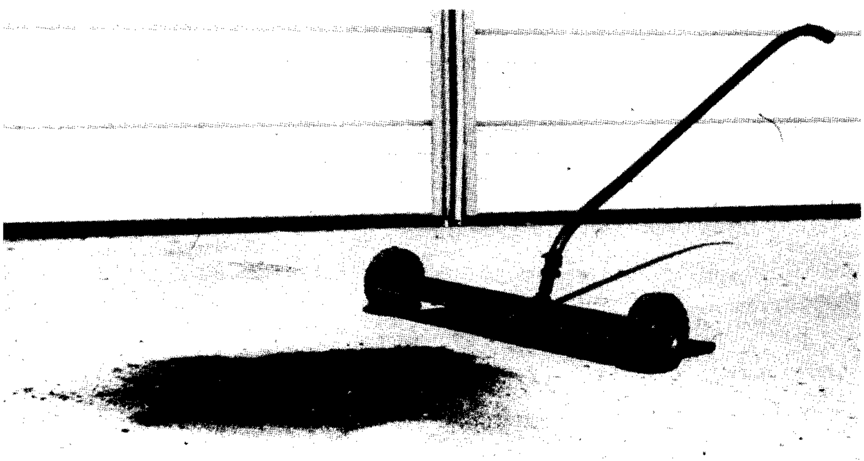

Figure 10.—Sweeper magnet used to extract tags from magnet scrapings.

adult fish were marked and released (Table 1).

Tagging efforts were shifted to adult Gulf menhaden in 1969. Emphasis was placed on determining if any extensive eastern or western movement took place within or between fishing seasons (Pristas et al., 1976). Tagging was conducted in three tagging areas (Fig. 12). During this study over 75,000 adult Gulf menhaden were tagged (Table 2).

Tagging of prerecruit juvenile menhaden in estuarine systems began on the Atlantic and Gulf coasts in 1970, but was preceded by some feasibility tagging activity in the New England area in 1969 (Kroger et al., 1971). The objectives of the juvenile studies were to delineate movement and recruitment patterns on

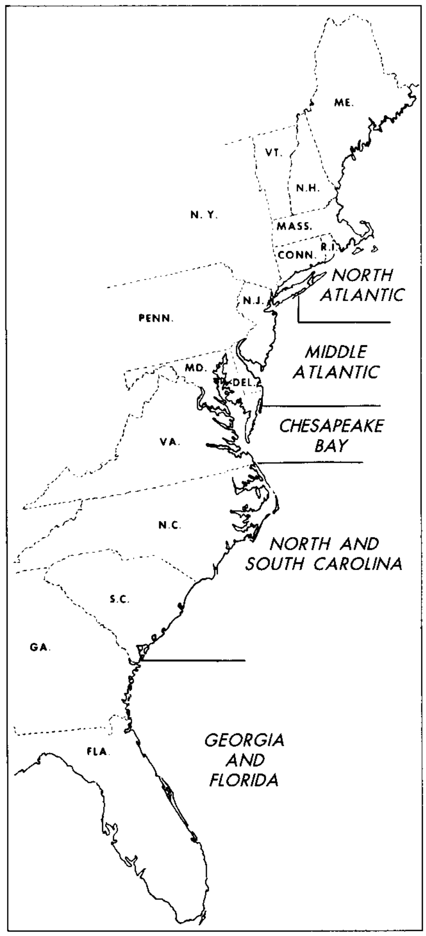

Figure 11.—Atlantic coast fishing areas and tag release areas for Atlantic menhaden.

Table 1.—Total releases of adult Atlantic menhaden marked with internal, ferromagnetic tags, by area and year, on the U.S. Atlantic coast (from Coston, 1971).

Year	Area: North Atlantic	Middle Atlantic	Chesapeake Bay	N. and S. Carolina	Georgia and Florida	Totals
1966	0	0	0	88,898	0	88,898
1967	2,093	13,660	100,128	159,077	95,832	370,790
1968	2,370	21,789	132,596	109,120	118,819	384,694
1969	8,468	700	75,581	29,076	108,150	221,975
Totals	12,931	36,149	308,305	386,171	322,801	1,066,357

Table 2.—Total releases of adult Gulf menhaden marked with internal ferromagnetic tags, by area and year, on the U.S. Gulf of Mexico coast (from Pristas et al., 1976).

Year	Area: Western	Central	Eastern	Totals
1969	11,198	5,799	18,101	35,098
1970	9,100	5,100	3,575	17,775
1971	7,400	5,200	10,200	22,800
Totals	27,698	16,099	31,876	75,673

Table 3.—Total releases of juvenile Atlantic menhaden marked with internal ferromagnetic tags, by state and year, on the U.S. Atlantic coast.

Year	State: Mass.	R.I.	Conn.	N.Y.	N.J.	Del.	Md.	Va.	N.C.	S.C.	Ga.	Fla.	Totals
1970	2,600	1,200	48	2,261	347	900	1,351	3,300	5,142	1,400	1,400	1,200	21,149
1971	3,000	2,894	1,100	3,500	3,500	2,400	2,300	4,500	5,764	2,700	453	1,000	33,111
1972	1,000	1,000	3,000	4,500	975	0	1,000	3,000	4,075	185	0	0	18,735
1973	5,000	4,000	0	0	0	1,069	1,500	3,100	3,033	0	0	0	17,702
1974	1,000	0	0	2,000	3,599	4,994	6,198	7,893	9,900	0	0	200	35,784
1975	0	0	0	0	0	2,000	5,200	6,695	1,000	0	0	0	14,895
1976	0	0	0	3,882	1,799	3,099	4,000	3,987	9,182	1,000	0	0	26,949
1977	0	0	0	0	400	4,000	4,300	6,000	9,000	3,000	0	0	26,700
1978	3,700	0	0	1,600	0	3,000	4,400	6,000	3,800	300	0	500	23,300
1979	0	0	0	0	0	3,400	5,600	8,500	5,500	0	0	0	23,000
1980	2,000	0	0	0	0	4,600	4,200	2,000	6,000	0	0	700	19,500
1981	0	0	0	1,800	0	4,200	6,700	4,000	5,600	1,000	0	0	23,300
1982	2,000	0	0	2,000	1,997	4,000	2,000	5,999	4,000	2,000	1,264	0	25,260
1983	0	0	0	0	2,999	3,994	7,193	3,898	8,100	0	0	0	26,184
1984	898	0	0	1,199	2,789	2,365	5,572	6,592	7,612	3,238	2,000	2,799	35,064
1985	0	0	0	3,000	1,000	1,200	6,399	6,198	11,939	1,852	1,061	2,000	34,649
1986	0	0	0	0	0	0	0	5,398	6,592	0	0	0	11,990
1987	0	0	0	0	0	0	0	7,000	4,000	0	0	0	11,000
Totals	21,198	9,094	4,148	25,742	19,405	45,221	67,913	94,060	110,239	16,675	6,178	8,399	428,272

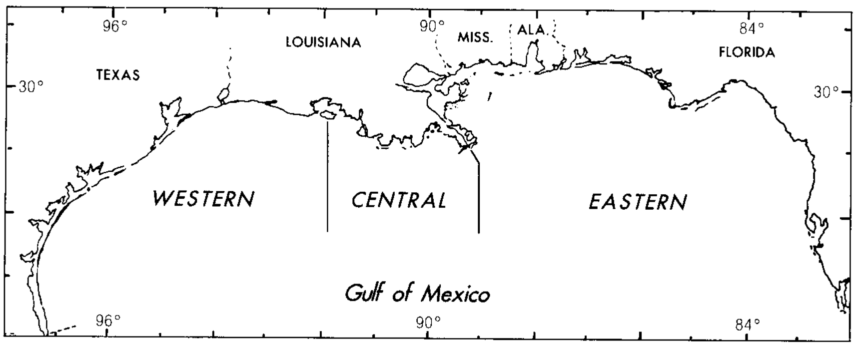

Figure 12.—Gulf of Mexico coast fishing areas and tag release areas for Gulf menhaden.

the basis of estuarine origin (Kroger and Guthrie, 1973). It was believed that with an improved knowledge of area specific recruitment rates coupled with area specific juvenile abundance estimates from another study (Ahrenholz et al., 1989), estimates of area-specific contributions to total recruitment could be obtained. Hence, the necessary parameters to estimate subsequent fishery recruitment and yield would be available (Kroger and Pristas, 1975). The number of tagged fish released are summarized by state for each coast (Tables 3, 4).

Refining the Mark-Recovery Data

Mark-recovery data in general require one or more types of quantitative adjustments to satisfy assumptions necessary for some analytical procedures, especially those that estimate population mortality rates or abundance. The internal ferromagnetic mark-recapture data share many analytical problems with external, visually detected, and voluntarily reported data, and have some more or less unique characteristics as well. The nature of the errors that can occur in parameter estimation when assumptions are not met are discussed in depth by Ricker (1975). Some of the errors are discussed with respect to mortality estimation for Gulf menhaden in Ahrenholz (1981).

Adjustments to Numbers Released

Tagging Mortality-Tag Shedding (Short Term)

Soon after tagging, some fish may die as a result of handling or tagging, or may simply shed their tag through the unhealed incision. Errors may result in some population parameter estimates derived from the recovery data if the number released is not reduced with an accurate estimate of tagging mortality. The NMFS conducted a series of marking-survival experiments (Kroger and Dryfoos, 1972), from which several applicable estimates of tagging loss (dead fish and shed tags) were obtained for juvenile and adult Atlantic menhaden. Estimates of loss for adult fish tagged with the large tag were 10 and 24% (experiments 3 and 4). Estimates of losses of 37% were obtained for juveniles (mean FL = 83 mm) tagged with the small tag and 54% for those tagged with the large

Table 4.—Total releases of juvenile Gulf menhaden marked with internal ferromagnetic tags, by state and year, on the U.S. Gulf coast.

Year	State					Totals
	Tex.	La.	Miss.	Ala.	Fla.	
1970	4,090	3,400	622	1,199	1,147	10,458
1971	4,463	5,749	1,099	2,500	1,600	15,411
1972	4,939	5,040	1,100	0	2,500	13,579
1973	0	0	0	0	4,400	4,400
1974	3,200	4,200	1,700	0	1,861	10,961
1975	0	0	0	0	0	0
1976	3,000	9,000	2,000	2,000	3,600	19,600
1977	7,000	6,900	0	0	9,600	23,500
1978	6,000	5,600	2,000	1,400	4,000	19,000
1979	4,000	0	0	0	0	4,000
1980	7,790	4,200	4,500	0	0	16,490
1981	4,978	4,000	2,000	2,000	4,800	17,778
1982	8,000	6,000	2,300	2,500	2,400	21,200
1983	7,579	1,792	2,986	1,000	2,000	15,357
1984	10,287	5,914	1,400	2,099	2,000	21,700
1985	10,471	6,000	2,000	2,000	3,031	23,502
Totals	85,797	67,795	23,707	16,698	42,939	236,936

tag (experiment 12). In a study conducted by the Louisiana Wildlife and Fisheries Commission (Byars, 1981) to estimate tagging loss among juvenile Gulf menhaden, an estimate of 30% loss was obtained for fish tagged with the small tag, and 35% for those (>90 mm fork length) tagged with the large tag. No studies of tagging mortality have been conducted with adult Gulf menhaden, but results should be similar to those obtained for the Atlantic menhaden.

Differential Mortality-Tag Shedding (Long Term)

Errors may also result when tags are shed at a more or less continuous rate over the lifespan of the fish, or if there is a differentially greater long-term mortality for tagged fish than for untagged fish. Studies to evaluate this type of potential error have not been conducted for either Atlantic or Gulf menhaden. However, losses from shedding should be minimal after the incision has healed (a few weeks as reported by Kroger and Dryfoos, 1972).

Differential Tagger Induced Mortality

Different taggers may induce a differential rate of short-term tagging mortality. Since there have been extensive field tagging programs with two or more taggers working side-by-side, this additional potential source of error can easily be evaluated. Although the short-term loss rate is assumed to be constant among taggers, occasionally differences are great enough to require special treatment. Adjustments for differential tagging mortality among taggers were made to some of the adult Gulf menhaden releases (Ahrenholz, 1981).

Adjustments to Numbers Recovered

Not all of the tags that enter a plant are recovered by the series of magnets. To estimate the tag recovery efficiency for a plant, test batches of 100 tagged dead fish were added to the plant landings at regular intervals during the fishing season. The number of test tag batches released at a given plant ranged from 1 to 30 during a fishing season, depending on the length of time the plant operated. Recovery efficiencies (number recovered divided by the number placed into the system) have been calculated for primary, or both primary and secondary magnets, depending on the intended analytical application. Estimates of the actual numbers of field-released tags which entered a plant are obtained by multiplying the number actually recovered by the inverse of the recovery efficiency.

Occasionally tags became lodged in the plant machinery and were recovered one or more seasons after the tags entered the plant. This source of error results in overestimates of total numbers of tags recovered for subsequent years. This type of recovery, although not uncommon, occurred at low enough rates that adjustments were not required for the earlier Gulf menhaden mark-recovery mortality analyses (Ahrenholz, 1981). Adjustments for lodged tags can, however, be made where necessary.

Behavioral Limitations

The determination of migratory patterns does not require data refinement. Unadjusted, primary recoveries are adequate for examining most migratory hypotheses considered. Migratory patterns that could be influenced by the fish's body size should still be reflective of the population as a whole, as the presence of the internal tag does not appear to affect growth rate (Kroger et al., 1974a). The two types of tagging studies (adults tagged on the fishing grounds and juveniles tagged in estuarine nursery areas) have proved to be complementary when examining for adherence to assumptions required for analytical procedures to estimate mortalities and abundances.

Program Accomplishments

The menhaden tagging programs and their resultant data sets have made major contributions to our knowledge of the biology and population dynamics of both the Atlantic and Gulf menhaden. Initially, returns from the adult program provided documentation for hypotheses of stock structure and migratory patterns (Ahrenholz, 1991). Estimates of M were subsequently obtained for each species from their mark-recapture data (Dryfoos et al., 1973; Ahrenholz, 1981; Reish et al., 1985). Data from the juvenile tagging programs permitted the determination of general recruitment patterns from estuarine nursery areas to the fishery. These collective results provided information necessary to construct and support stock assessment analyses for each species (Nelson and Ahrenholz, 1986; Ahrenholz et al., 1987).

The mark-recapture program has provided direct, highly visible answers to stock structure and recruitment questions that have been understandable and acceptable to many laymen and industry members. The characteristically high information content of tagging data have made these results desireable for use by analysts as well. Because of this high level of credibility and information, these data are extremely useful for supporting management-oriented analyses.

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The Atlantic and Gulf Menhaden Purse Seine Fisheries: Origins, Harvesting Technologies, Biostatistical Monitoring, Recent Trends in Fisheries Statistics, and Forecasting

JOSEPH W. SMITH

Origins

The menhaden fishery is one of the oldest and largest commercial fisheries in the United States. Beginning in colonial times, seine fisheries for Atlantic menhaden, *Brevoortia tyrannus*, were established at various sites along the New England coast. Beach seines were the principal gear, the fisheries were localized, and whole fish from the catch were sold for fertilizer. Frye (1978) recounts that techniques for boiling and pressing menhaden were developed in Rhode Island by 1811. Press machinery yielded fish oil which was used in various industrial processes and as a fuel oil, while the dried, pressed fish mass known as fish scrap was sold as fertilizer. By 1845 purse seines were introduced to the New England area (Frye, 1978) and the fishery, no longer dependent on localized abundance of fish schools or beach seining sites, expanded into nearshore coastal waters. After the Civil War menhaden reduction plants were established in Virginia and North Carolina. By about 1895 a scarcity of fish north of Cape Cod caused a collapse of the fishery in New England, and by the early 1900's the industry was concentrated in the Middle and South Atlantic states (Nicholson, 1971). During this period fish "scrap" was still the principal product of the industry, with each company producing its own formula of fertilizer. Harrison (1931) reported that by the late 1920's much of the menhaden catch was milled into farm animal feed, while the amount of fertilizer produced declined, fish oil was used "in the manufacture of soap, linoleum, water-proof fabrics, and certain types of paints".

Spurred by increased demand for fish meal mainly from the burgeoning "broiler" poultry industry, the years immediately following World War II mark the birth and development of the modern menhaden industry and purse seine fleet. This period also marks the inception of the Gulf menhaden, *B. patronus*, purse seine fishery, as many established companies on the Atlantic coast moved some or all of their operations to the U.S. Gulf coast to fish that virtually unexploited stock.

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ABSTRACT—With its genesis in New England during the 1800's, the purse seine fishery for Atlantic menhaden, Brevoortia tyrannus, *expanded south and by the early 1900's ranged the length of the eastern seaboard. The purse seine fishery for Gulf menhaden,* B. patronus, *is of relatively recent development, exploitation of the stock beginning in the late 1940's. Landings from both fisheries annually comprise 35-40% of the total U.S. fisheries landings, ranking menhaden first in terms of volume landed. Technological advances in harvesting methods, fish-spotting capabilities, and vessel designs accelerated after World War II, resulting in larger, faster, and wider-ranging carrier vessels, improved speed and efficiency of the harvest, and reduction in labor requirements. Chief products of the menhaden industry are fish meal, fish oil, and solubles, but research into new product lines is underway. Since 1955 on the Atlantic coast and 1964 on the Gulf coast, the NMFS has monitored the fisheries for biostatistical data. Annual data summaries of numbers-of-fish-at-age harvested, catch tonnage, and fishing effort of the fleet form the basis of routine stock assessments and annual catch forecasts to industry for the upcoming fishing season. After landings declined in the 1960's, the Atlantic menhaden stock has recovered through the 1970's and 1980's. Exceptional year classes of Gulf menhaden in recent years account for record landings during the 1980's.*

The crew of a schooner, in an old-style seine-boat, throws the purse seine around a school of menhaden.

Due to corporate consolidations, acquisitions, and plant closures in recent years, the present-day menhaden fishery is comprised of only a few major companies. Vessels, gear, and to some extent spotter aircraft are company owned. Vessels, in particular, are specifically designed for menhaden fishing, and as such are generally not used in other fisheries. The menhaden industry is vertically integrated with most companies marketing their chief products—fish meal, fish oil, and solubles—directly to brokers or feed milling companies; compared to most other U.S. fisheries, handling and processing technologies in the menhaden industry are relatively advanced (GSMFC, 1983).

Harvesting Technologies

Purse seine fishing for menhaden is a daylight activity, prosecuted in nearshore coastal waters, generally less than 15 m (50 feet) deep. The basic pattern of fishing begins with a carrier vessel which searches for or is directed to concentrations of menhaden schools. Upon location, two purse boats, each carrying one-half of the seine, are lowered from the carrier vessel. The purse boats encircle the school with the seine (Fig. 1), then tighten the purse line, which runs along the bottom of the seine, enveloping the school. Hydraulic power blocks assist retrieving the wings of the seine. The fish are concentrated into the bunt of the net, then loaded onboard the carrier vessel, and at day's end they are transported to the reduction plant. Catch per purse seine set (which is a good estimate of school biomass) may range from a few to over 50 t (Nicholson, 1971), and sets of over 150 t are not uncommon.

By present standards purse seining in the nineteenth century was laborious and inefficient, with carrier vessels being

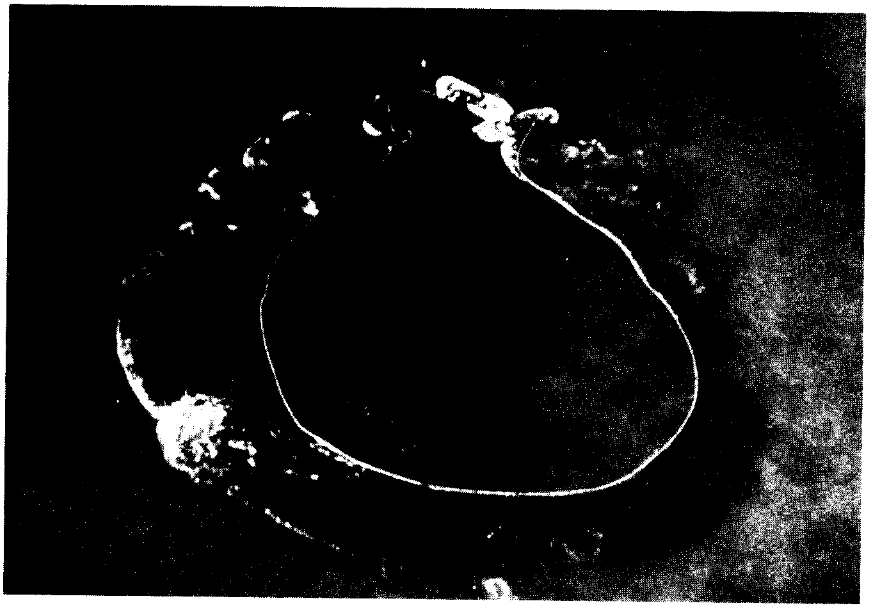
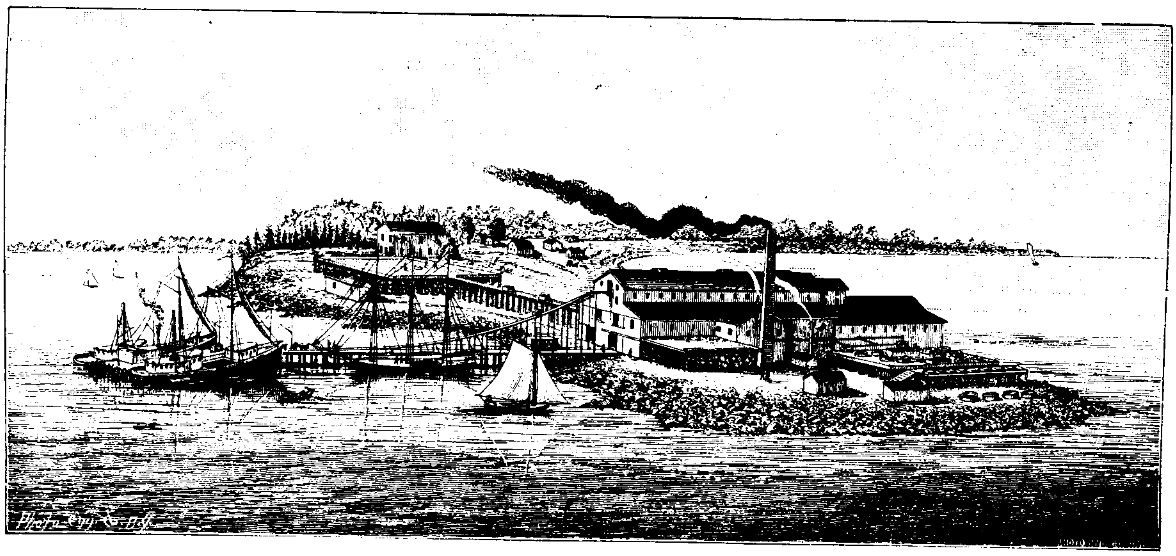
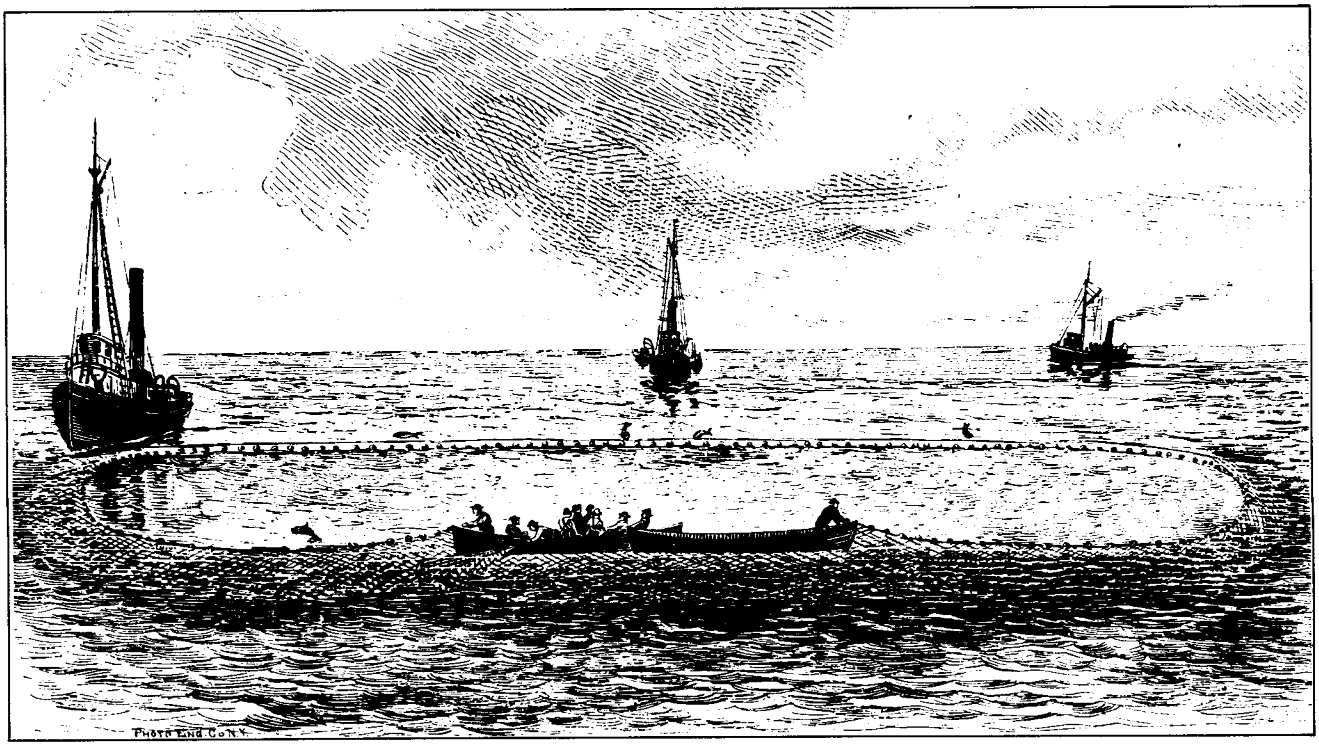


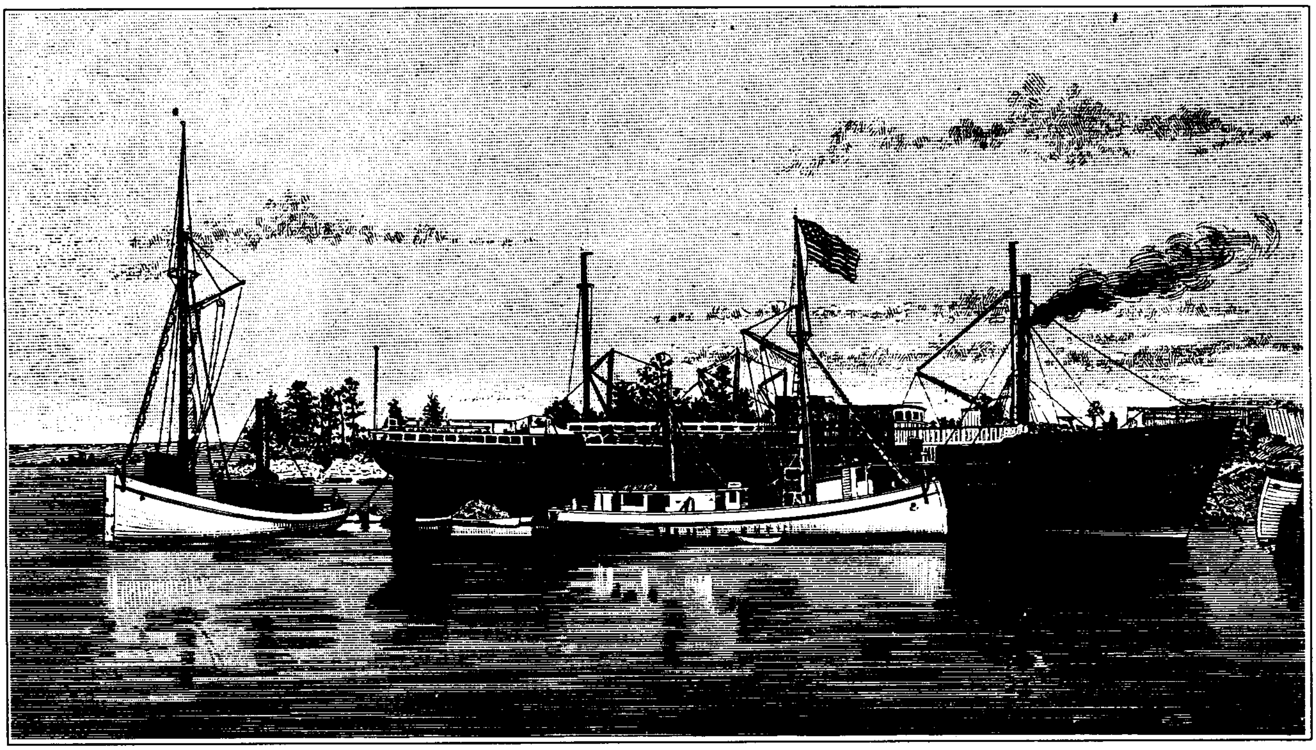
Figure 1.—Aerial view of a menhaden purse seine set. Photograph by Hall Watters, formerly of Standard Products Co., Reedville, Va.



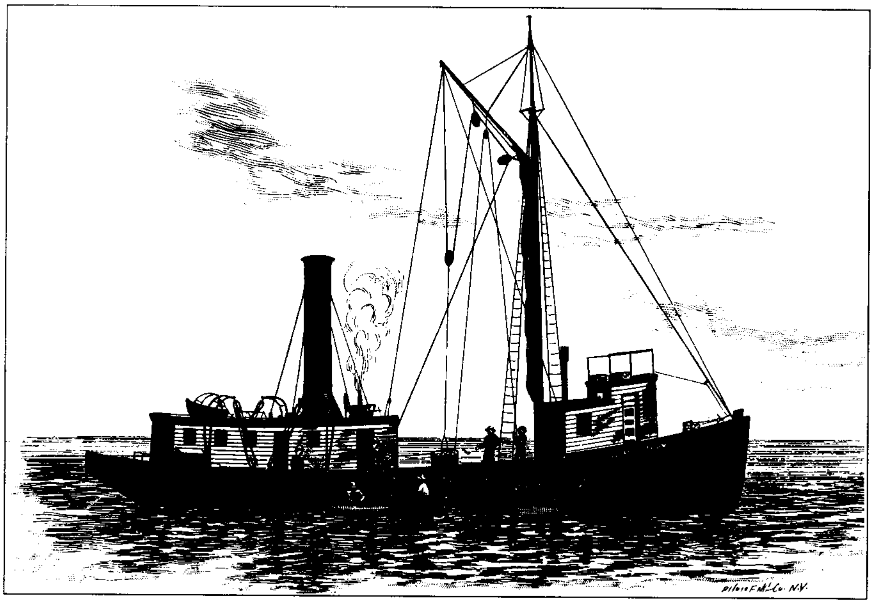
An early menhaden and guano factory at Milford, Conn., showing steamers unloading fish at the wharf, an incline railway for carrying fish to cooking tanks on the upper floor of the factory, oil tanks and storage sheds in the foreground, and a platform for drying scrap in the rear of the factory connected with the building by elevated railway.



Menhaden strike the net as a school is surrounded with a purse seine.



Floating menhaden factory: An old vessel was fitted as an oil factory and was moved from place to place near the fishing grounds.



An early menhaden steamer bails in the catch.

sailed and purse boats being rowed (Nicholson, 1971). By the turn of the century, larger carrier vessels were fitted with steam engines, and the purse boats were powered by gasoline engines. After World War I, diesel and gasoline engines powered the carrier vessels. Following World War II and paced by the rising demand for fish meal, numbers and sizes of vessels increased.

Although basic menhaden purse seining methodologies have remained unchanged for decades, innovations in gear, handling, and vessel design and technologies have vastly improved the efficiency of the modern menhaden fleet. Major changes in harvesting technologies after World War II were chronicled by Nicholson (1971, 1978). In 1946 spotter airplanes were introduced into the fishery. Initially, they directed the fleet to large concentrations of fish, but later they were equipped with two-way radios and airplane pilots actually directed the setting of the net. Spotter aircraft are single-engine, overhead fixed-wing planes; some are privately owned by the pilots, while others are owned or leased by the menhaden companies. Pilots usually fly a "patrol" in late afternoon or early evening to locate concentrations of fish for the next day's fishing activities. Vessel captains are alerted to the approximate locations of the fish schools, and are expected to be on fishing grounds at dawn where they are joined by the spotter. Pilots are adept at judging not only the size (volume) of the fish school, but also the size of the fish within the school. One aircraft may guide several vessels.

By the late 1950's aluminum purse boats began replacing wooden purse boats. Aluminum purse boat hulls are lightweight and much more maneuverable and faster than the wooden design. Modern purse boats measure about 11-12 m (36-40 feet) long, 3 m (10 feet) wide, and are powered by a diesel engine which also furnishes power to the hydraulics. Most carrier vessels transport their purse boats aft on davits swung overboard. A recent modification to a few menhaden vessels features davits that not only raise and lower the purse boats via hydraulic winches, but additionally the davits pivot inboard so that the purse boats rest in deck cradles on the stern (Anonymous, 1987). With this design, purse boat crews can board and disembark the purse boats more easily and safely, and time and effort are saved when docking and undocking (most carier vessels must disembark their purse boats coming to dockside). Also, a recent modification to menhaden vessels features purse boats that rest on an inclined stern ramp while in transit, again eliminating the danger of boarding purse boats at sea (Anonymous, 1988).

Hydraulic power blocks (Schmidt, 1959) were introduced to the fishery in the mid-1950's and were utilized by nearly the entire fleet by the mid-1960's. A power block, mounted on a hydraulically operated crane in each purse boat, facilitates concentrating the catch in the bunt of the net and the quick retrival of the "wings" of the net after a set. The difficult task of retrieving the net by hand was eliminated, and purse boat crews were reduced from about 22 to 12 deckhands.

Nylon seines replaced natural fiber nets by the mid-1950's. Synthetic netting is stronger, has less tendancy to burst when a large catch is made, and hence requires less repair time. Approximate dimensions of modern purse seines used by the menhaden fishery are 19-22 mm (¾-⅞ inch) bar mesh, up to 365 m (1,200 feet) long, and 18-27 m (60-90 feet) deep.

After the catch is concentrated or "hardened-up" in the bunt of the net, the carrier vessel comes alongside the net and purse boats to load the fish into the hold. Large fish pumps, standard equipment on most carrier vessels since the mid-1950's, rapidly transfer fish to the hold and replace the laborious method of brailing the catch. A flexible, 10-inch hose is lowered into the bunt and suction draws fish and water onto the carrier vessel. Fish pass over a de-watering screen, then into the hold.

With the evolution of the menhaden fleet in the Gulf of Mexico came the need to refrigerate the catch and prevent rapid decomposition of menhaden during the warm Gulf coast summer. As developed, chilled seawater is constantly sprayed over the catch and recirculated to a refrigeration unit through screens in the floor of the hold. Refrigerated fish holds were introduced to the Gulf menhaden fleet in 1957 (Nicholson, 1978), and by 1972 all Gulf menhaden vessels had refrigeration. Presently, most vessels in the Atlantic fleet have refrigeration, the benefits of which are twofold: Not only is the quality of the catch preserved, but trip duration and range from home port are increased.

Since the mid-1950's the number of carrier vessels in the Atlantic menhaden fleet has declined dramatically from about 150 to 22 to 1987; the Gulf menhaden fleet has been more stable, numbering about 60-80 vessels over the same period (see the Recent Trends section). Despite the downward trends in total number of menhaden purse seiners, since the 1950's trends in vessel construction have been toward larger, faster, and more efficient carrier vessels. After World War II, decommissioned military craft, many of which were steel-hulled, were retrofitted and became the progenitors of the modern menhaden fleet. By about the mid-1950's, larger steel carrier vessels designed specifically for menhaden fishing began replacing the smaller and aging wooden-hulled vessels of 1930's and 1940's vintage (Fig. 2). Modern steel purse seiners are longer, have greater fish hold capacities, are faster (greater main engine horsepower ratings), and have better amenities for the crew than their earlier counterparts (Table 1). Most modern menhaden vessels are company-owned, and since some companies manage several plants at different ports, occasionally vessels are reassigned to alternate plants depending upon the availability of fish. Crew size is generally 15-16, with captain, mate, pilot, engineers, cook, and deckhands. All of the innovations above have served to reduce search time, loading time, and labor costs, while increasing vessel range, trip duration, and load capacity and quality.

Most modern carrier vessels homeported along the Gulf coast, in Chesapeake Bay, and to some extent New England and the South Atlantic, have retained the classic lines of a menhaden purse seiner (Fig. 3), that is, bridge, mess, crew's quarters and crows' nest forward, fish holds amidships, and engine room aft; these vessels generally range from 43 to 52 m (140-170 feet) long and 250-375 net t. Exceptions to the traditional menhaden purse seiner design occur on the Atlantic coast. In Chesapeake Bay a few smaller carrier craft (less than about 30 m (100 feet) and 100 net t) employ a purse-seine variation called a "snapper rig" in which usually one purse boat is used. These vessels are unrefrigerated and generally fish in areas where larger carrier vessels cannot venture. Most of the catch is sold as bait, although some is sold for reduction. In New England, since menhaden are usually only available during summer, carrier vessels until recently were multiple-use craft (generally trawlers or draggers) that convert to purse seining in summer. The catch is not refrigerated, but is offloaded for reduction at day's end. In recent years

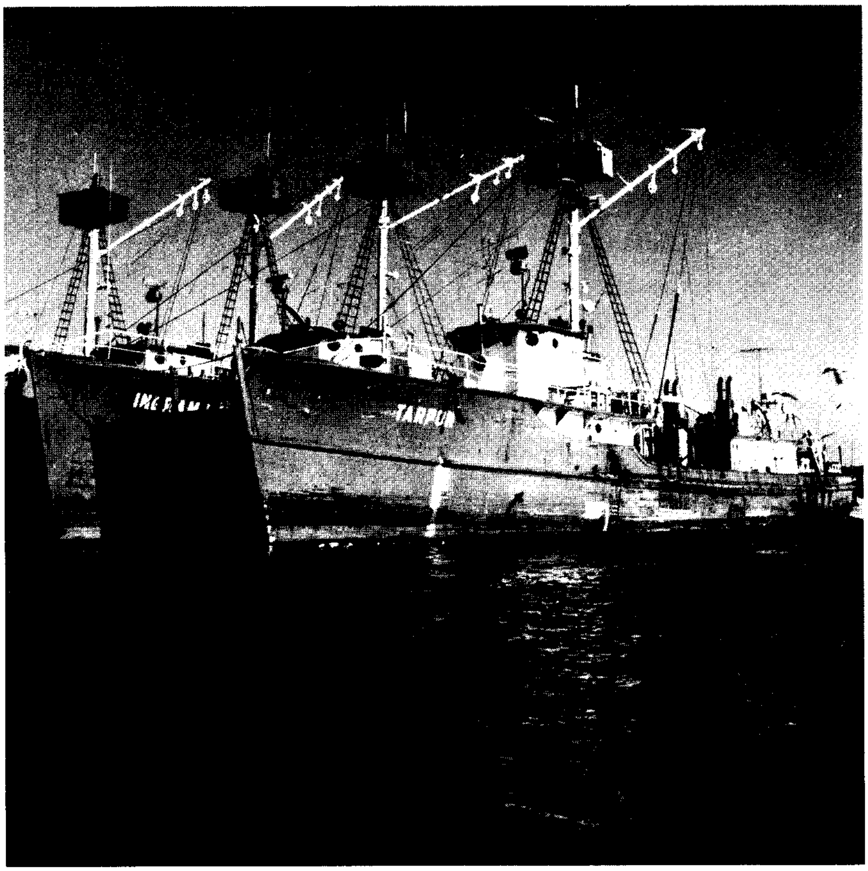


Figure 2.—Wooden-hulled menhaden purse seine vessels of about mid-1940's vintage.

Table 1.—A comparison of fleet characteristics for the Atlantic and Gulf menhaden purse-seine fisheries, 1980 vs. 1988.

	1980				1988			
	Atlantic menhaden fishery, 44 Vessels[1]		Gulf menhaden fishery, 78 Vessels[2]		Atlantic menhaden fishery, 21 Vessels[1]		Gulf menhaden fishery, 72 Vessels[2]	
Item	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Length (feet)	68-200	148	124-195	156	87-200	164	126-195	161
Gross tons	92-754	427	181-648	445	151-754	531	199-746	493
Net tons	64-615	286	103-453	304	115-564	363	139-615	337
Horsepower	480-2,000	1,384	440-2,320	1,381	720-2,000	1,638	440-2,450	1,534
Age (years)	11-46	39	1-36	14	1[3]-44	35	1[3]-44	22
Season's catch (t)	1,560-16,000	8,700	1,300-16,500	9,000	2,700-18,900	13,900	1,100-15,400	8,600

[1] Includes only vessels that landed regularly in the summer fishery; excludes vessels added in fall and converted trawlers in the North Atlantic area.
[2] Includes vessels that landed fish 9 or more weeks of the 26 week season.
[3] Newest additions to the menhaden fleet are former oil rig supply boats converted into purse seiners (see Anonymous, 1987).

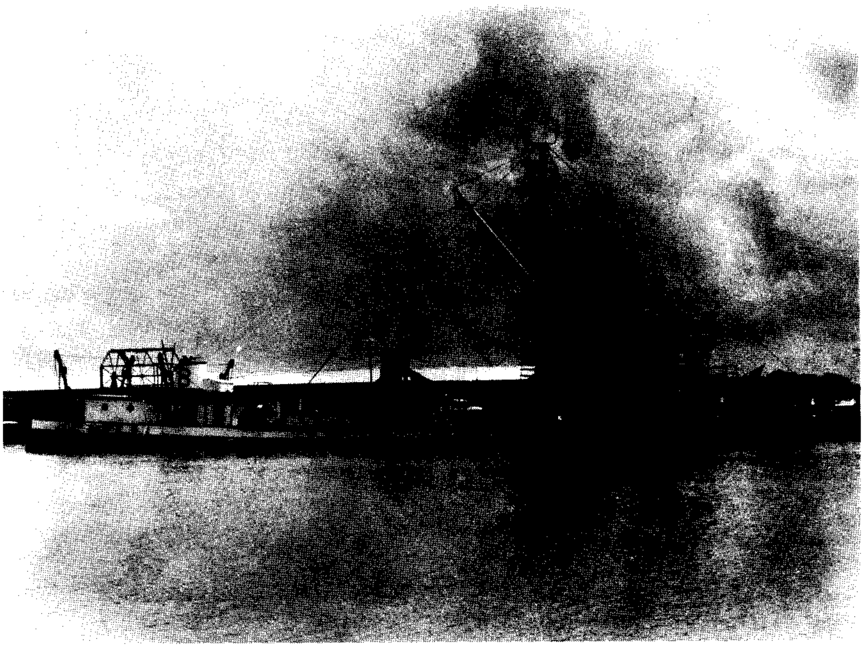


Figure 3.—F/V *Carl Burton* at dockside prior to offloading a full fish hold of Gulf menhaden (Photograph by R. B. Chapoton, 1968).

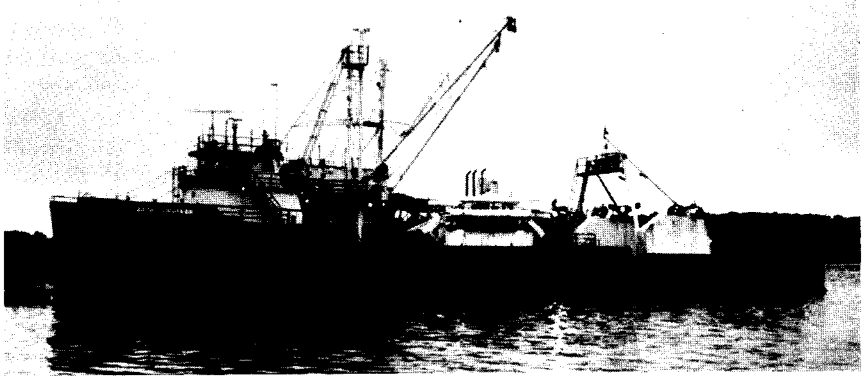


Figure 4.—F/V *Coastal Cruiser*, a menhaden purse seiner, formerly an oil-rig supply vessel.

several steel-hulled, modern purse seiners have joined the menhaden fleet in New England. In the South Atlantic, a few shallow draft vessels less than 30 m (100 feet) long fish primarily in sounds and large bays. They are unrefrigerated and tow their purse boat. A recent innovation in the fleet has been the conversion of surplus oil rig supply vessels to purse seiners (Fig. 4) (Anonymous, 1987, 1988). By 1989, about 12 of these converted vessels had joined the menhaden fleet.

Industrial Processes and Major Products

The wet reduction process whereby menhaden are processed into fish meal, fish oil, and fish solubles varies from plant to plant mainly in the manner which fish are shunted through the facility (Fig. 5, 6). Despite increased efficiency and capacity within certain menhaden plants, the basic rèduction process has changed little since outlined by June and Reintjes (1976). The following descriptions of menhaden reduction facilities and processes are gleaned from their work, ASMFC (1981), and GSMFC (1983).

At dockside with a day's catch, the hold of the carrier vessel is partially flooded with water. Fish and water are evacuated through openings in the floor of the fish hold, and moved shoreside via suction through a large diameter hose primed by a fish pump. Several "bailers" constantly agitate and direct fish toward the drain in the fish hold using jets of water sprayed from hoses. This washdown water is recycled through the entire offloading process and is eventually moved to storage tanks as "stickwater" (see below). On shore, fish pass over a dewatering screen and then into a rotating hopper. Each compartment of the hopper volumetrically contains 0.36 m^3 (22,000 $inches^3$). In industry jargon, one compartment or "dump" of the hopper holds 1,000 "standard" fish, or gravimetrically 304 kg (670 pounds); a few plants on the Gulf coast employ hoppers that hold 1,500 "standard" fish or 456 kg (1,005 pounds). By convention one "standard" fish weighs 0.3 kg (0.67 pound). Wages of captains, crews, and to some extent airplane spotter pilots, are based on the number of "dumps" offloaded.

Fish are transferred from the hopper by conveyor belts, draglines, or augers to either the cookers or a temporary holding bin called the "raw box". Fish usually are not held over 12 hours in the raw box. Drag lines in the floor of the raw box convey fish into the cooker where fish are subjected to jets of steam. Cooked fish mass is then transferred to screw presses where water, oil, and soluble elements (i.e., press liquor) are squeezed out. Cooked fish mass after pressing is called press cake. Press liquor from the presses is pumped into centrifuges where aqueous and oil fractions are separated. Fish oil is eventually pumped to storage tanks, while the aqueous fraction or "stickwater" passes through evaporators which concentrate

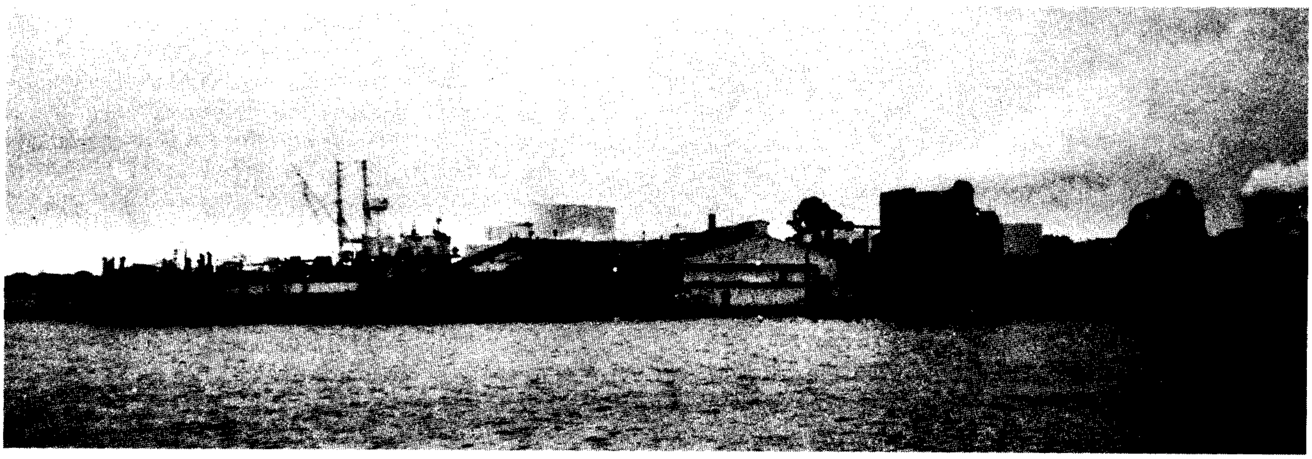


Figure 5.—A modern menhaden reduction factory in Reedville, Va.

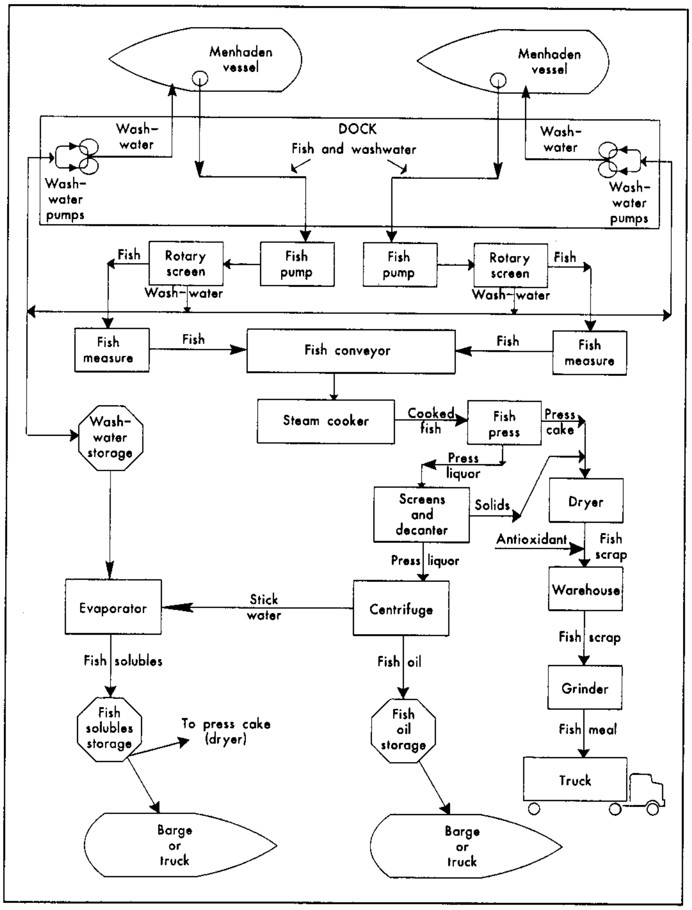


Figure 6.—Schematic diagram of a menhaden reduction plant (from ASMFC, 1981).

the fraction to a syrup-like consistency. The resulting condensed fish solubles (containing about 30% protein, 10% fat, and 10% minerals) are either stored in tanks or reincorporated into the press cake prior to the drying process. End product meal from this route is referred to as whole or full meal. Press cake is passed to rotary steam or direct heat dryers and dried to fish "scrap" with a minimum desired content of 60% protein, 10% fat, and about 20% minerals and 10% moisture. Dried fish scrap is transferred by overhead conveyors to large piles on the floor of the storage shed. At some point in this transfer, an antioxidant is added to the fish scrap to prevent caking and loss of product quality, and to promote cooling. Fish scrap is ground to fish meal by a hammermill prior to shipping via truck, railroad car, or barge. Fish oil is shipped in the same fashion.

Although in some years a small percentage is exported, most menhaden fish meal becomes a valuable ingredient in domestic animal feeds. The poultry industry, followed by the swine industry, utilizes a majority of the annual production of menhaden fish meal in feed formulas. Feed formulas vary by milling company and area, but up to 8% of broiler chicken ration may be menhaden fish meal. Other common constituents milled into feeds include corn, soy, meat, and bone meal. In recent years significant amounts of menhaden meal have been milled into aquaculture feeds for catfish, trout, salmon, and shrimp.

Inexplicably, during the 1940's, menhaden fish oil was omitted from legislation listing suitable oils permitted for human consumption in the United States.

Thus, most menhaden fish oil is exported to Europe and Canada where it has been used for decades as an edible oil. After deodorization, hydrogenation, and blending with other oils, it is marketed as a cooking oil or margarine. Domestically, small quantities of menhaden fish oil are refined and become valuable components of lubricants, plasticizers, resins, and paints. It also has use as a supplemental fat source in animal feeds.

Menhaden solubles are generally reintroduced to the press cake to make a "full" fishmeal. Solubles are also milled into various feeds to enhance their nutritional value, or mixed into liquid feed supplements.

In recent years (data available for 1980-85: AMAC, 1986) small but significant quantities of Atlantic menhaden (up to about 4,000 t/year) have been taken by purse seine and sold either fresh or frozen for crab bait. Purse seine landings of Atlantic menhaden for bait occur mainly in Massachusetts, New Jersey, Virginia, and North Carolina. A purse seine bait fishing operation targeting Gulf menhaden has also recently been established in Louisiana.

Beside these traditional uses of menhaden products, the industry has recently moved toward the development of new product lines (Hale et al., 1991). Increased demand for Japanese surimi-based seafood products has stimulated feasibility studies to determine the suitability of menhaden for surimi production (Lanier, 1985). Research into uses of menhaden oil for human food and medicinal markets is also underway (Hale et al., 1991).

Biostatistical Monitoring

The Beaufort Laboratory of the Southeast Fisheries Science Center, National Marine Fisheries Service (Bureau of Commercial Fisheries prior to 1970), NOAA, began preliminary sampling of the Atlantic menhaden purse seine fishery in the Middle Atlantic and Chesapeake Bay areas between 1952 and 1954 (June and Reintjes, 1959), and expanded the sampling design to encompass the entire range of the Atlantic fishery in 1955. During the early 1960's, program managers were concerned that the Gulf menhaden resource might be overfished and extensive sampling of the Gulf menhaden purse seine fishery was instituted in 1964 (Chapoton, 1971). Sampling programs on both coasts have since continued uninterrupted. Early sampling strategies concluded that fish of similar size and age school together. It was estimated that a 20-fish sample was adequate to estimate the mean size of fish in a purse seine set (June and Reintjes, 1959). Seasonally hired port agents were instructed to sample a bucket of fish from the top of the fish hold (after discarding the top veneer of fish that may have desiccated). It was assumed that fish on the top of the hold represented the vessel's last set of the day (not necessarily the entire boatload). Location and date of the last set were ascertained from the captain or a crew member. One hundred fish were sequentially selected from the sampling bucket. Each fifth fish (20 fish per sample) was measured (fork length, mm), weighed (g), sexed, and scales removed for ageing (June and Roithmayr, 1960). By the late 1960's, menhaden program managers realized that age and size variability of specimens within vessels was less than that among vessels (Chester, 1984). Beginning in 1972 on both coasts, port agents were responsible for acquiring more samples per week (up to 20-25 per port), but sample size was cut to 10 fish and specimens were no longer sexed. The sampling program has remained relatively unchanged since the early 1970's, with only minor modifications. With the increased importance of Chesapeake Bay and North Carolina landings to the Atlantic fishery, and ranging of the fleet to adjacent fishing areas, sampling activity was increased in those areas during the 1980's during months of peak landings. In recent years (1983-88), the average number of 10-fish samples processed has been 875 samples (8,750 fish) per year for the Atlantic menhaden fishery and 1,492 samples (14,920 fish) per year for the Gulf menhaden fishery.

The menhaden companies on both coasts provide confidential daily landings and effort data, usually on a monthly basis. Daily vessel landings by plant are reported in values representing the number of "dumps" of the hopper per vessel offloading (1 dump = 304 kg or 670 pounds). The factor 0.3039 (670 pounds/2204.62 pounds), is multiplied by the number of dumps to get metric tons offloaded. Monthly landings by plant are added to get season totals.

Nominal or observed fishing effort is derived from daily plant records. The unit of nominal fishing effort for the Atlantic menhaden fishery is the "vessel week," that is, one vessel landing fish at least one day of a calendar week. Total nominal effort is the sum of the number of vessel weeks for all Atlantic vessels. The unit of nominal fishing effort for the Gulf menhaden fishery is the "vessel-ton week," that is, the product of a vessel's net registered tonnage multiplied by a vessel week. Total nominal effort for the fishery is the sum or vessel-ton weeks for all vessels in the fleet. Since, on average, large vessels in the Gulf menhaden fleet catch more fish than small vessels, the vessel-ton week explains some of the differences in efficiency within the Gulf menhaden fleet, more so than the vessel-week unit used for the Atlantic menhaden fleet (Schaaf et al., 1975).

Estimates of number of fish in the landings by coast are calculated by a computer program (Huntsman and Chapoton, 1973). Number of fish at each age caught each week at each plant (or combination of plants at the same port) are calculated on the basis of weight of the sampled fish, their ages, and the weekly vessel landings. Weekly numbers at age are added to get monthly and annual totals. Annual estimates of numbers of fish at age form the basis of menhaden stock assessments and population analyses (e.g., Ahrenholz et al., 1987; Vaughan, 1987).

Between 1955 and 1965, in an effort to better describe effort in the fishery and identify location of purse seine sets, logbooks were placed on Atlantic menhaden purse seine vessels at the beginning of each fishing season. Captains were requested to list number, location, and size of daily sets. Port agents were to pick up logbooks biweekly. In most years, over 60% of the fleet participated. Major results of this survey are reported in Nicholson (1971). A similar logbook survey was conducted on the Gulf coast between 1964 and 1969. Locations of over 48,000 purse seine sets were recorded, the results of which are reported in Nicholson (1978).

Beginning in 1978 and continuing through the present, the menhaden industry and Federal and state agencies jointly devised a second logbook project called the Captain's Daily Fishing Report (CDFR's). Among other things, CDFR's request information on location of sets, start and stop time of individual sets, estimate of number of fish per set, and weather conditions. Since 1978, Atlantic menhaden vessels have logged over 39,000 CDFR's and Gulf menhaden vessels over 123,000 CDFR's. Key entry of CDFR data for several years has been completed with limited analyses conducted for selected data sets.

Recent Trends in Fisheries Statistics

Atlantic Menhaden Fishery

Temporally, the Atlantic menhaden fishery is usually partitioned by the industry into two distinct fisheries, the "summer" and "fall" fisheries. The summer fishery usually begins about April or May as surface schools appear off northern Florida and the Carolinas. By mid-to-late May, fishing in Chesapeake Bay commences, and by June schools migrate into New England waters. Peak coastwide landings occur from June to September. By early fall, schools begin to move south and fishing in New England waters usually ceases by late September. Early November signals the beginning of the fall fishery and large schools of all age and size classes concentrate as they round the North Carolina capes. The intensive fall fishery usually ends by mid-January as schools disappear south of Cape Lookout, N.C. Historically, most fall landings have been made at North Carolina ports, but in recent years vessels from Chesapeake Bay have exploited fall migratory fish as far south as Cape Hatteras.

Atlantic menhaden stratify during summer along the U.S. east coast by size and age, with older and larger fish moving farther north. Typical age composition of the landings in recent years by geographic area are:

Table 2.—Number of reduction plants, purse-seine vessels, and landings (1,000 t) for the Atlantic and Gulf menhaden fisheries, 1955-88.

	Atlantic menhaden[1]			Gulf menhaden[2]		
Year	Plants	Vessels	Landings	Plants	Vessels	Landings
1955	23	150	641.4	9	72	215.0
1956	24	149	712.1	10	81	244.8
1957	25	144	602.8	10	73	159.9
1958	22	130	510.0	10	77	201.5
1959	23	144	659.1	11	73	335.3
1960	20	115	529.8	10	75	380.7
1961	20	117	575.9	10	69	459.5
1962	19	112	537.7	12	74	480.7
1963	17	112	346.9	11	73	437.8
1964	18	111	269.2	11	76	409.4
1965	17	84	273.4	13	82	463.1
1966	20	76	219.6	13	80	359.1
1967	18	64	193.5	13	76	317.3
1968	17	59	234.8	14	69	373.5
1969	15	51	161.6	13	72	523.7
1970	15	54	259.4	13	73	548.1
1971	14	51	250.3	13	82	728.2
1972	11	51	365.9	11	75	501.7
1973	11	58	346.9	10	65	486.1
1974	10	63	292.2	10	71	587.4
1975[3]	12	61	250.2	11	78	542.6
1976	11	62	340.5	11	82	561.2
1977	12	64	341.1	11	80	447.1
1978	12	53	344.1	11	80	820.0
1979	12	54	375.7	11	78	777.9
1980	11	51	401.5	11	79	701.3
1981	11	57	381.3	11	80	552.6
1982	11	47	382.4	11	82	853.9
1983	10	41	418.6	11	81	923.5
1984	8	38	326.3	11	81	982.8
1985	6	24	306.7	7	73	881.1
1986	5	16	238.0	8	72	822.1
1987	6[4]	23	327.0	8	75	894.2
1988	6[4,5]	30	309.3	8	73	623.7

[1] Data for 1955-85 from Smith et al. (1987a).
[2] Data for 1955-84 from Smith et al. (1987b).
[3] For fishing years 1975-79, menhaden were landed at Pt. Judith, R.I., and trucked to South Portland, Me. Facility at Pt. Judith counted in Atlantic menhaden plant totals.
[4] Includes reduction plant in New Brunswick, Can.
[5] Includes Soviet factory ship, Maine-U.S.S.R. cooperative venture.

1) In the North Atlantic area (eastern Long Island through the Gulf of Maine), mostly age-3 fish with some older fish up to age-6;

2) In the Middle Atlantic area (western Long Island to Chincoteague, Va.), mostly age-2 and age-3 fish;

3) In the Chesapeake Bay area, age-1 and age-2 with some age-3;

4) In the South Atlantic area (Cape Hatteras to northern Florida), age-1 and age-2; and

5) In the North Carolina fall fishery, age-0 through age-8 may occur, although this segment of the fishery is highly weather dependent.

To understand recent trends in the Atlantic menhaden fishery, Ahrenholz et al. (1987) described stock status in terms of several temporal stanzas. The 1950's were described as years of stock expansion: The age structure broadened, and several dominant year classes entered the fishery. Landings surpassed 500,000 t in 1953 and peaked at 712,000 t in 1956, the record year for the Atlantic menhaden fishery (Table 2; Fig. 7). By 1962, dominant year classes of the previous decade disappeared from the fishery. The remainder of the 1960's was without a dominant year class; the stock's age structure began to contract and became severely truncated by 1967. Landings fell to 162,000 t by 1969. Improving recruitment during the 1970's gradually added significant numbers of older fish to the fishery. During the late 1970's landings rose to 378,000 t, and by the 1980's the stock showed signs of strengthening and significant expansion (1983 landings reached 419,000 t). Landings in 1986 fell to 238,000 t, but the decline was more indicative of prevailing economic conditions in the fishery, and a major plant in Virginia temporarily closed for the season. By 1987 the economic climate had improved, the closed plant reopened, and landings reached 327,000 t.

Estimated total numbers of Atlantic menhaden in the landings declined from a record 5.35 billion in 1959 to 0.87 billion in 1969 (Table 3). Landings gradually improved during the 1970's and by 1983, 3.94 billion fish were landed. The fishery has always relied heavily on prespawning fish (age 2 and younger), but despite the rebound in estimated numbers of fish landed, age composition of the landings changed considerably. Between 1955 and 1962, the annual percentage (by numbers) of prespawners in the landings averaged 83% (range: 51-96%), whereas between 1975 and 1987, the annual percentage of prespawners in the landings averaged 94% (range: 87-98%). Additionally, unprecedented numbers of age 0 menhaden or "peanuts" were taken in 1979, 1981, and 1984, mostly during the North Carolina fall fishery.

After the Atlantic menhaden stock declined precipitously in the early 1960's and fish became scarce in the northern half of their range, many plants north of the Chesapeake Bay closed (Nicholson, 1975). During the 1970's significant numbers of fish again appeared in

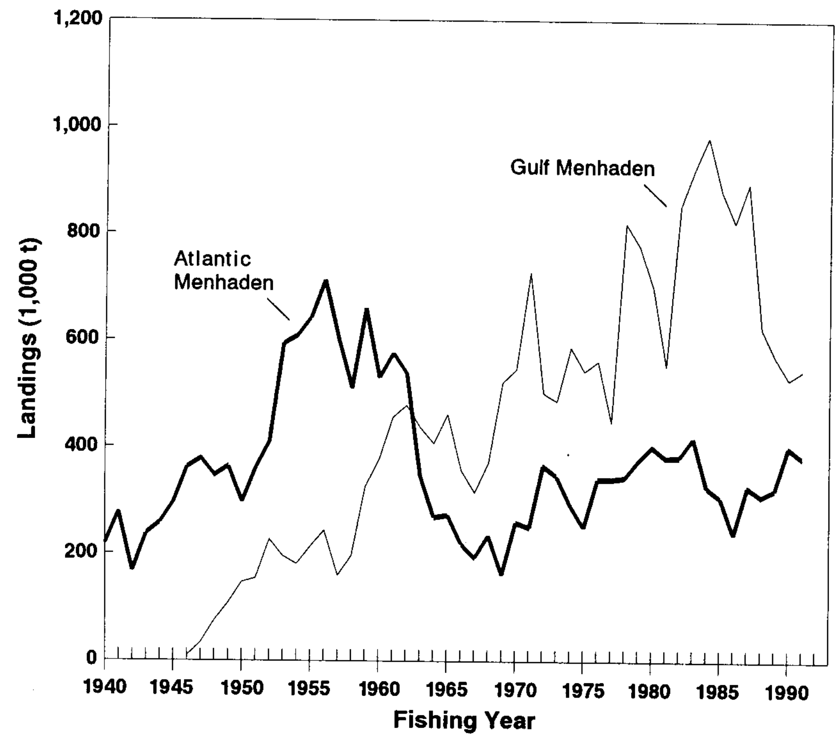


Figure 7.—Historical landings of Atlantic (1940-91) and Gulf menhaden (1945-91) by purse seine for reduction.

Table 3.—Estimated numbers (millions) of Atlantic menhaden by age landed by purse-seine vessels, 1955-88.

Year	Number by age									Total no. (millions)
	0	1	2	3	4	5	6	7	8-10	
1955	761.01	674.15	1,057,68	267.31	307.21	38.07	10.53	1.84	0.64	3,118.44
1956	36.37	2,073.26	902.72	319.60	44.78	150.68	28.70	6.72	1.99	3,564.82
1957	299.58	1,599.98	1,361.77	96.73	70.80	40.52	36.93	4.26	1.10	3,511.67
1958	106.06	858.16	1,635.35	72.05	17.25	15.94	9.09	4.88	0.43	2,719.21
1959	11.40	4,038.72	851.29	388.27	33.41	11.87	12.36	4.55	1.77	5,353.64
1960	71.17	281.01	1,208,63	76.37	102.20	23.77	7.95	2.36	0.65	2,775.11
1961	0.25	832.42	503.60	1,209.57	19.18	29.38	2.86	0.81	0.24	2,598.31
1962	51.58	514.11	834.52	217.25	423.37	30.75	24.60	2.98	0.70	2,099.86
1963	96.89	724.23	709.20	122.53	44.97	52.38	10.42	3.33	0.56	1,764.51
1964	302.59	703.95	604.98	83.50	17.94	7.85	6.62	1.31	0.32	1,729.06
1965	249.12	745.21	421.40	77.76	12.19	1.81	1.22	0.75	0.06	1,509.50
1966	349.45	550.99	404.22	31.70	3.85	0.36	0.19	0.11	0.04	1,340.83
1967	6.95	678.29	266.97	72.87	5.09	0.48	0.01	0.00	0.00	1,030.67
1968	173.75	309.72	466.22	65.24	10.67	0.98	0.06	0.00	0.00	1,026.65
1969	158.13	377.33	284.31	47.81	5.44	0.15	0.01	0.00	0.00	873.18
1970	21.42	870.85	473.92	32.63	4.02	0.11	0.00	0.00	0.00	1,402.96
1971	72.85	263.29	524.32	88.29	17.84	2.51	0.00	0.00	0.00	969.96
1972	50.16	981.27	488.47	173.06	19.12	1.86	0.00	0.00	0.00	1,713.95
1973	55.98	588.47	1,152.94	38.63	7.00	0.34	0.00	0.00	0.00	1,843.36
1974	315.55	636.68	985.97	48.59	2.49	1.35	0.00	0.00	0.00	1,990.63
1975	298.64	719.96	1,086.53	50.24	6:63	0.20	0.10	0.00	0.00	2,162.30
1976	274.23	1,611.96	1,341.09	47.97	7.95	0.28	0.00	0.00	0.00	3,283.47
1977	484.62	1,004.54	2,081.77	83.46	17.80	1.41	0.11	0.00	0.00	3,673.71
1978	457.41	664.09	1,670.91	258.12	31.19	3.48	0.00	0.00	0.00	3,085.20
1979	1,492.46	623.14	1,603.29	127.93	21.76	1.47	0.09	0.00	0.00	3,870.13
1980	88.29	1,478.06	1,458.23	222.71	69.23	14.36	1.44	0.00	0.00	3,332.32
1981	1,187.57	698.66	1,811.46	222.20	47.47	15.37	1.27	0.00	0.00	3,984.02
1982	114.11	919.44	1,739.55	379.67	16.33	5.78	0.53	0.32	0.00	3,175.72
1983	964.41	517.22	2,293.06	114.35	47.37	5.01	0.23	0.00	0.46	3,942.11
1984	1,294.22	1,024.17	892.09	271.50	50.34	15.21	0.51	0.00	0.00	3,548.04
1985	637.19	1,075.85	1,224.62	44.06	35.63	6.25	1.68	0.00	0.00	3,025.29
1986	100.28	224.99	1,527.45	48.72	10.18	6.38	1.15	0.00	0.00	1,919.16
1987	44.93	541.78	1,652.04	143.87	25.47	2.23	0.75	0.00	0.00	2,411.08
1988	429.16	314.09	1,180.64	309.28	70.74	6.77	0.52	0.23	0.00	2,311.43

New England waters and as many as four plants were active in the North Atlantic area (plants in this area primarily process fish offal from the New England trawl fisheries, but also process menhaden during summer). By winter 1988, however, plants at Pt. Judith, R.I., Gloucester, Mass., South Portland, Maine, and Rockland, Maine, had closed, not because of a scarcity of fish, but due to social problems of fish factory operation in densely populated urban areas. Beginning in 1987, a plant in New Brunswick, Can., began receiving menhaden for reduction, and by 1989 it was the only shoreside plant processing menhaden from the Gulf of Maine (Fig. 8). During 1988 and 1989, a cooperative venture between a company in Maine and the Soviet Union allowed processing of menhaden for reduction onboard a Soviet factory ship anchored off Maine. Actual fishing operations, however, were performed by up to twelve U.S. vessels.

The recent closure of reduction plants along the New England coast, and to some extent the Middle Atlantic coast, appears symptomatic of a trend referred to as "waterway gentrification"[1]. Revitalization of urban harbor areas along the U.S. "northeast corridor" has led to increasing demands for waterfront space and properties; nontraditional waterfront users, such as restaurants, shopping malls, and condominium/marina complexes now compete with traditional user groups such as commercial fishing enterprises, and in general are capable of paying the most for waterfront space (Houlahan, 1987). Menhaden reduction factories with their associated (but not insurmountable) air and water effluent controversies are often deemed less than desirable when adjacent to trendy waterfront developments. Thus, local governments have moved to restrict odor emissions from plants and, in some instances, forced plant closures. In New England a recent solution to the enigma of an abundance of menhaden in coastal waters without shoreside processing facilities has been the advent of a near-

[1] Lippson, R. 1987. Natl. Mar. Fish. Serv., NOAA, Oxford Lab., Oxford, Md. Presentation entitled, "Waterway gentrification" given at annu. meet. Tidewater Chapt., Am. Fish. Soc., Nov. 15-17, Atl. Beach, N.C.

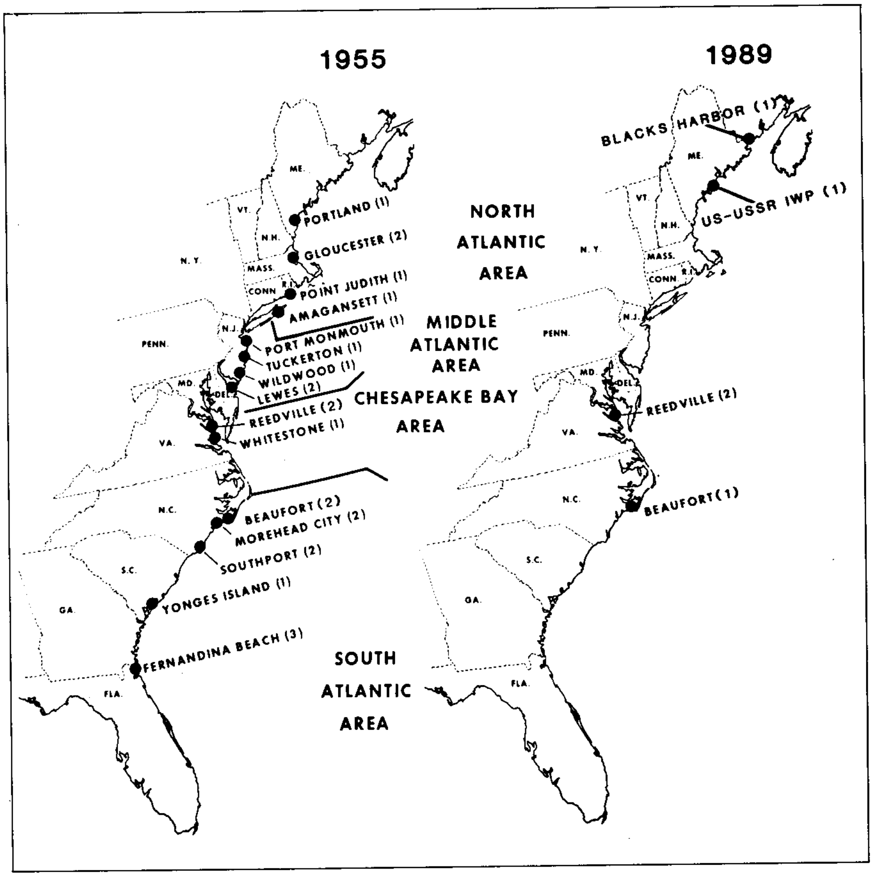


Figure 8.—Location of reduction factories for Atlantic menhaden, 1955 vs. 1989.

shore factory ship operated by a Maine-U.S.S.R. cooperative venture.

In the Middle Atlantic area as many as five plants were active during the early 1960's, but through the 1970's only one plant at Port Monmouth, N.J., operated; it closed after the 1981 season. During 1973-85, two plants in the Chesapeake Bay area were active, both in Reedville, Va.; one temporarily closed in 1986, but reopened in 1987. In the South Atlantic area and during the North Carolina fall fishery, three plants in Beaufort, N.C., were active during 1973-84, but one plant only operated intermittently during summer and a second closed after the 1986 season. A plant in Southport, N.C., was active during 1972-83 and also participated intermittently in the North Carolina fall fishery before closing in 1983. A small plant at Fernandina Beach, Fla., was active through 1986 before it closed in July 1987.

Total number of vessels in the Atlantic menhaden fleet fell from 150 in 1955 to 51 in 1971. The number of vessels then increased slightly to 64 in 1977, but declined further to 38 vessels in 1984. During 1987, 24 vessels were active in the Atlantic menhaden fleet. Declines in number of vessels in the fleet in recent years reflect: 1) Closure of several plants in the North and South Atlantic areas and 2) decisions by major companies to retire older and inefficient wooden-hulled vessels.

Gulf Menhaden Fishery

Gulf menhaden exhibit an inshore-offshore migratory pattern with surface schools appearing in nearshore coastal waters as early as March and remaining into November before moving to deeper offshore waters to winter. Historically, a few landings have occurred in March and November. However, in 1977 four of the five Gulf states voted in favor of a cooperative regional management plan (GSMFC, 1983) that limited the fishing season to a 26-week period, beginning in mid-April and ending by mid-October. Peak landings occur between May and August.

Prior to World War II, purse seine landings of Gulf menhaden were few and sporadic, annually ranging from 2,000 to 12,000 t between 1918 and 1944 and were landed in Florida, Mississippi, and Texas (Nicholson, 1978). During the late 1940's, new reduction plants were built in Mississippi, Louisiana, and Texas and landings increased to 103,000 t by 1948. As larger, more efficient vessels entered the fishery and fishing technologies improved, landings steadily increased, reaching 481,000 t by 1962. By 1963 annual Gulf menhaden landings exceeded Atlantic menhaden landings, a trend which continues through the present (Fig. 7). Between 1963 and 1981, Gulf menhaden landings ranged from 316,000 to 820,000 t (Table 2). Beginning in 1982 and for 6 consecutive years, landings exceeded 800,000 t, with record landings for Gulf menhaden of 983,000 t in 1984.

Between 1964 and 1987, annual estimates of the number of Gulf menhaden landed ranged from 4.24 billion fish in 1966 to 11.15 billion fish in 1985 (Table 4). The fishery harvests almost exclusively age 1 and age 2 Gulf menhaden, and over the sampling period the combined age classes annually averaged 96% of the fish landed by number. Age 1 fish annually contributed an average of 63% (range: 45-76%), and age 2 fish contributed an average of 33% (range: 19-45%). Age 0, age 3, and age 4+ usually comprise less than 5% of the landings.

Through the 1950's, between 9 and 11 menhaden plants operated in Florida, Mississippi, Louisiana, and Texas (Table 2). During the 1960's, 10-14 plants were active, but after 1971 menhaden reduction plants were located exclusively in Mississippi and Louisiana. Between 1972 and 1983, the number of plants stabilized at 10-11. In 1984 one of the largest menhaden processors acquired its closest competitor, thus gaining ownership of 7 of the 11 active plants in the Gulf of Mexico. Consolidation followed in 1984-85, with plants closing in Moss Point, Miss., Morgan City, La., and Cameron, La. Also in 1985, economic conditions forced the temporary closing of a plant at Empire, La., reducing active plants to 7. During 1986-88, four companies operated 8 plants in Mississippi (2) and Louisiana (6). In 1989, a ninth plant opened in Morgan City, La. (Fig. 9).

During the late 1940's, the Gulf menhaden fleet increased rapidly from 10 to 53 vessels. The fleet increased slowly through the 1950's to a peak of 82 vessels in 1965. Between 1966 and 1984, fleet size varied from 65 to 82 vessels. After the corporate consolidation in 1984, the fleet declined to 73-75 vessels in 1985-88.

The unit of nominal or observed fishing effort in the Gulf menhaden fishery is the vessel-ton week. As the fleet grew in numbers and size, nominal effort gradually increased and by 1969 reached the 400,000 vessel-ton-week level. By 1975 nominal effort for the fishery climbed above 500,000 vessel-ton weeks, and peaked in 1983 at 655,800 vessel-ton weeks.

Forecasting

In 1972 the Beaufort Laboratory was asked by the menhaden industry to provide annual forecasts for upcoming Atlantic and Gulf menhaden fishing seasons because, with a forecast, the industry could better plan its next year's operations. Program biologists decided upon a multiple linear regression approach to forecasting menhaden catches as a function of effort anticipated in the fishery and catch and effort in previous years. Development and description of the model are recounted in Schaaf et al. (1975). Initially, the model was used to estimate catches for past years (pre-1973) on the Atlantic coast and was deemed satisfactory in estimating or "hindcasting" historic catches (coefficient of determination, $r^2 = 0.85$). Application to upcoming fishing seasons began in 1973 for both coasts and

Table 4.—Estimated numbers (millions) of Gulf menhaden by age landed by purse-seine vessels 1964-88.

Year	Number by age 0	1	2	3	4+	Total no. (millions)
1964	2.76	3,329.28	1,495.15	118.07	4.35	4,949.61
1965	43.43	5,031.39	1,076.63	80.27	0.70	6,232.41
1966	30.45	3,314.42	865.16	33.76	0.26	4,244.05
1967	22.44	4,267.65	337.66	13.00	0.00	4,640.74
1968	65.06	3,475.23	1,001.30	37.45	0.50	4,579.55
1969	20.80	6,075.00	1,286.34	31.66	0.00	7,413.81
1970	50.19	3,279.85	2,279.98	36.08	0.00	5,646.10
1971	21.59	5,761.13	1,955.45	181.84	4.12	7,924.12
1972	19.11	3,047.74	1,733.53	88.54	4.03	4,892.95
1973	49.90	3,033.00	1,106.98	99.62	1.27	4,290.77
1974	1.41	3,846.75	1,471.65	59.08	0.00	5,378.89
1975	108.77	2,440.51	1,499.21	461.83	0.19	4,510.51
1976	0.00	4,591.39	1,373.94	203.92	0.00	6,169.25
1977	0.00	4,659.95	1,331.72	110.37	5.63	6,107.66
1978	0.00	6,787.44	2,742.01	52.67	5.24	9,587.37
1979	0.00	4,701.22	2,877.16	337.20	6.81	7,922.39
1980	65.86	3,409.41	3,261.11	436.15	47.86	7,220.39
1981	0.00	5,750.53	1,424.94	329.40	34.22	7,539.08
1982	0.00	5,146.74	3,301.96	503.54	62.26	9,014.50
1983	0.00	4,685.73	3,809.23	382.61	25.10	8,902.67
1984	0.00	7,749.55	2,881.49	438.36	49.75	11,119.14
1985	0.00	8,127.64	2,723.64	283.04	20.58	11,154.90
1986	0.00	4,266.16	5,022.44	186.36	25.17	9,500.13
1987	0.00	5,936.61	4,528.74	396.13	12.36	10,873.84
1988	0.00	5,568.62	2,799.45	164.68	13.20	8,545.95

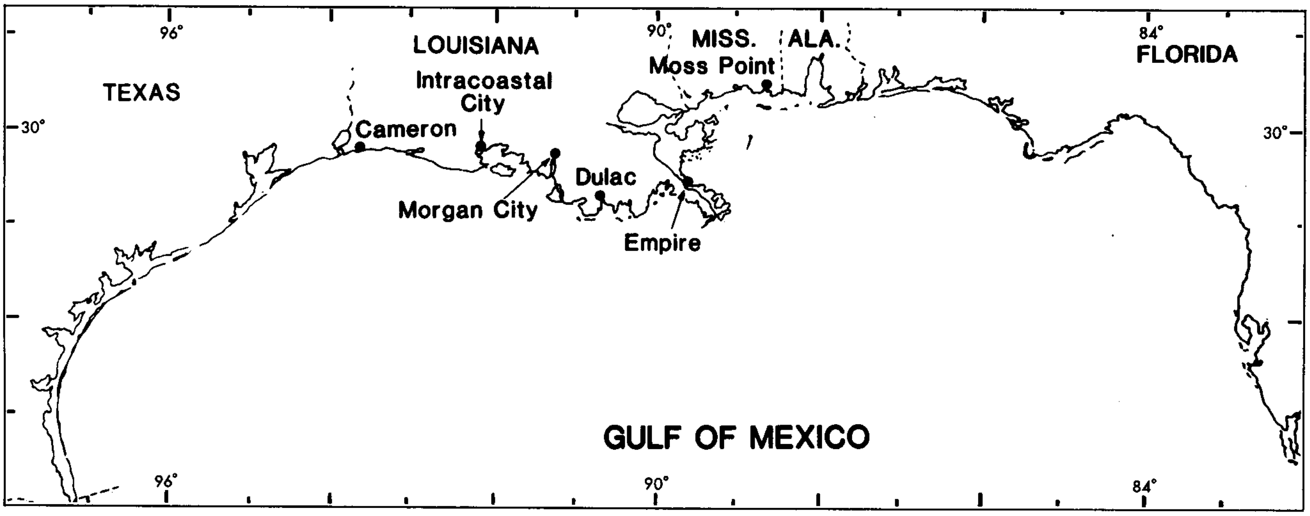


Figure 9.—Location of reduction factories for Gulf menhaden, 1989.

1989 marked the seventeenth consecutive year of forecasts. Written forecasts take two forms:

1) In late November a preliminary forecast is released for the next year's fishing season based on estimates of catch and effort for the just-completed Gulf menhaden season and the ongoing Atlantic menhaden season; and

2) In mid-April a formal forecast is released based on finalized catch and effort values from the previous season's activities on both coasts and expected effort in the upcoming season.

Forecasts of landings for the upcoming fishing year are conditioned on estimates of expected effort which are primarily derived from 1) industry input (i.e., the number of vessels that companies expect to be active during the forthcoming year) and 2) historical performance (effort) of the vessels expected in the fishery. Through the period 1973-88, our preseason estimates of fishing effort have differed from actual year's-end effort values an average of 8.4% for the Atlantic menhaden fishery and 4.1% for the Gulf menhaden fishery. To measure the accuracy of our forecast equation, we generate a hindcast at season's end, using the actual fishing effort for the season and then compare the hindcast to actual landings. For the Atlantic menhaden fishery using observed effort, actual purse-seine landings have differed an average of 10.8% from those forecast for the sixteen-year period 1973-1988 ($r^2 = 0.84$); similarly, landings for the Gulf menhaden fishery have differed from those forecast by an average of 15.8% for the same period ($r^2 = 0.88$).

As noted by Schaaf et al. (1975), our statistical model performs satisfactorily on average for forecasting menhaden landings. It will not predict sudden and large changes in catch, and offers no explanation for such. Recent studies by Jensen (1976, 1985) and Schaaf and Chester[2] strive to improve the predictability of menhaden forecasts using autoregressive models.

[2]Schaaf, W. E., and A. J. Chester. Forecast strategies for Atlantic menhaden catch. Unpubl. manuscr. on file at Beaufort Lab., SEFSC, Natl. Mar. Fish. Serv., NOAA, Beaufort, NC 28516-9722.

Summary

The menhaden purse-seine fishery, with its origins in New England during the mid-1800's, is one of the oldest and largest commercial fisheries in the United States. By the early 1900's, the fishery for Atlantic menhaden was established as far south as the Carolinas and northern Florida. The post-World War II years mark the inception of the Gulf menhaden fishery, and with it the modernization of the fisheries on both coasts. Technological advances in fishing gear and vessel design and construction have steadily increased the speed, range and efficiency of menhaden carrier vessels. Modern design changes within menhaden reduction plants increased efficiency and capacity. Menhaden meal, menhaden oil, and solubles continue to be the industry's chief products. Most meal and solubles are sold and incorporated into animal feeds, primarily poultry feed. Most menhaden oil continues to be exported to Europe and Canada where it is refined into margarine or cooking oil. Development of new menhaden products, such as surimi for analog foods and refined oils for human consumption and medicinal markets, hold promise for future diversification of the menhaden industry.

NMFS menhaden biostatistical sampling programs have been conducted for over three decades on the Atlantic coast and over two decades on the Gulf coast. Research has determined that during the 1970's and 1980's stock size and recruitment of Atlantic menhaden increased and age composition broadened, reversing trends witnessed during the fishery decline in the 1960's. Landings steadily improved through the 1970's, and by 1983 coastwide landings reached 418,000 t. Through the 1970's and 1980's, the Chesapeake Bay fleet has dominated the fishery in landings and fishing effort. Economic problems plagued the fishery in the mid-1980's and several plants closed temporarily. Numerous plant closures in New England and the Middle Atlantic area epitomize the modern fishery's dilemma regarding coastal development.

The Gulf menhaden fishery through the late 1970's and early 1980's has remained relatively stable with 11 reduction plants and about 80 carrier vessels. After 1984 a major corporate acquisition reduced the number of plants to 8 and the number of vessels to about 73. Beginning in 1982 and for six consecutive years total Gulf menhaden landings have exceeded 800,000 t, and in 1984 record landings for the fishery were produced, 982,800 t. Exceptional landings through 1987 are related to increased stock size due to large year classes entering the fishery in the late 1970's and 1980's.

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New Products and Markets for Menhaden, *Brevoortia* spp.

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Introduction

The search for new, higher valued products and markets for menhaden, *Brevoortia* spp., utilization has become more urgent because of the uncertain economic future of the fish meal and oil industry. Meal and oil prices recovered sharply between 1986 and 1988, but have dropped significantly since 1988. Price competition from soybean meal continues. Menhaden oil also faces price competition, and the traditional market in Europe is uncertain. Menhaden represented 23.5% of U.S. commercial fishery landings in 1989 but less than 2.6% of the total value (NMFS, 1990). There is a definite need for new value-added food products and there have been several recent developments that are pertinent. These include: 1) The construction and operation of a menhaden surimi experimental demonstration plant, 2) the submission of a petition to the U.S. Food and Drug Administration for use of menhaden oil in food products in this country, and 3) extensive publicity and heightened interest in the health benefits of omega-3 fatty acids.

ABSTRACT—Although menhaden, Brevoortia *spp., represent 23.5 percent of United States commercial fishery landings, they represent only about 2.6 percent of the total landed value of fishery products. New food products and markets are needed to increase the economic value of the menhaden resource. This paper describes investigations of menhaden as a raw material for both traditional and new forms of food products. Canned menhaden is a logical food product, but the production of a menhaden surimi with good functionality has recently been demonstrated. The U.S. Food and Drug Administration has placed partially hydrogenated menhaden oil on the GRAS list of ingredients for food products, but a decision on the status of nutritionally beneficial refined menhaden oil is not yet available. Refined menhaden oil is currently the raw material for biomedical test materials being used in research approved by the National Institutes of Health to determine the health benefits of fish oils and omega-3 fatty acids. The test materials are being produced, with strict quality controls, at the NMFS Charleston Laboratory.*

Menhaden Characteristics

Physical and Sensory Characteristics

A majority of U.S. consumers have never heard of menhaden, and most of those who have are of the opinion that menhaden are inedible or at least unsuitable for human food. Menhaden are generally small, contain many fine bones, and have a high oil content. Yearly averages vary, but Atlantic menhaden, *B. tyrannus*, may range from 100 to 150 g and Gulf menhaden, *B. patronus*, from 80 to 120 g in the bulk of the catch in a typical harvest season.

Menhaden contain large amounts of highly unsaturated fatty acids that are prone to rapid oxidation. They have a reputation for rapid spoilage. It has been shown, however, that if menhaden are chilled rapidly and held at about 0°C they can produce good food products in appropriate product forms (Hale and Ernst, 1986).

Chemical Composition

The oil content of menhaden, as with other members of the herring family, varies greatly by season. Moisture varies with fat content, and the two combined are equal to about 80 percent of the total constituents. Protein content of whole menhaden is generally within the range of 15-17%, while the edible flesh averages about 18-19% protein. Dubrow et al. (1976) reported proximate and fatty acid compositions for Atlantic menhaden over the 1967-1969 seasons. Monthly average fat contents peaked in October at about 21% while the overall mean value was 14.4% fat. The fat content of Atlantic menhaden delivered to the surimi demonstration plant in 1987 peaked in October, but at less than 12% (Bimbo et al., 1988).

Miller et al. (1986) reported proximate compositions for ten different collections of Gulf menhaden in 1984. Fat contents ranged from 9.9 to 22.5% with a mean value of 14.2%. They also reported proximate and amino acid compositions and yields for several dressing, processing, and waste material fractions as well as for the whole Gulf menhaden.

Joseph (1985) reported fatty acid profiles for both Atlantic and Gulf menhaden oil samples collected during the 1982 and 1983 seasons. Monthly composite oil samples were supplied by three commercial reduction plants on the Atlantic coast and nine commercial plants on the Gulf coast. Annual mean values for major fatty acids were similar, within experimental variation, for Atlantic and Gulf oils. There were, however, some highly significant differences between seasonal samples of Gulf menhaden oils. Bimbo (1989) has also reported fatty acid profiles from Atlantic and Gulf menhaden oils.

Appropriate Product Forms

Menhaden are not suitable for the standard fresh or frozen fillet markets because of their bone content and susceptibility to lipid oxidation. Successful food products must be processed in a manner

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to eliminate these problems. Appropriate product forms include canned products, to soften bones and protect against oxidation, and surimi, with mechanical separation of bones and removal of oxidation catalysts by washing. The special properties of menhaden oils also point to promising commercial products. The substantial omega-3 fatty acid content of menhaden oil may have significant nutritional and/or therapeutic benefit as a constituent of appropriate food products. Protection from oxidation is, of course, essential. There are a number of other potential menhaden products which are discussed in this paper.

New Protein Products in Traditional Forms

Canned Products

Canned small pelagic fish species make a significant contribution to world protein supplies, and a truly international market has developed for them since World War II (Lanier, 1981). Menhaden fit the definition for small pelagic species as contained in Lanier's FAO report: "...commonly characterized by their abundance...density of schools, comparatively high fat content, and the very different properties (particularly oil and fat content) of individual fish between seasons." Canning is a particularly appropriate preservation method for fish such as menhaden because the bones are softened during heat processing and the sealed can protects against lipid oxidation (Fig. 1). Lightly smoked and canned menhaden were reported to have very good sensory acceptability (Hale and Ernst, 1986). Dressed, filleted, and minced forms of menhaden were canned and evaluated by Johnson et al. (1988). Fillets packed in oil or broth, or dressed menhaden (brined for a firmer texture) were said to have the highest potential. The market for canned fish is highly competitive, but it represents a realistic possibility for utilization of menhaden for food. The use of menhaden oil as a canning medium could provide health benefits based on its content of important omega-3 fatty acids. At the National Marine Fisheries Service (NMFS) Charleston Laboratory, we have evaluated some excellent experimental sardines (herring packs), prepared by a commercial company using a refined, deodorized menhaden oil rather than a vegetable oil (Bimbo, 1988a).

Figure 1.—Canning is an appropriate process for the use of menhaden as food.

Preserved Products

In addition to the familiar early use of menhaden as fertilizer, many menhaden were preserved for food by salting in early 19th century America. More recently the development of salted, dried products prepared from several species, including Atlantic menhaden, were reported. However, the salted dried menhaden did not generate interest at an Asian trade show (Huang et al., 1986).

The smoking of menhaden produces a desirable flavor, but bones are a problem in menhaden that are smoked but not heat processed. Menhaden may also be pickled to produce products similar to those prepared with Atlantic herring, *Clupea harengus*.

Sausage Products

Fish sausages are a common food product in Japan but not in the United States. Efforts have been made for several years to have minced fish approved as an ingredient in frankfurters. Experimental frankfurters containing minced fish or surimi from several different species have recently been prepared at the NMFS Charleston Laboratory and supplied to the U.S. Department of Agriculture for nitrosamine analyses and analytical methods development. They have developed a new, more accurate analytical method and have shown that nitrosamines are not the problem that was earlier indicated for franks containing nitrite and minced fish. Frankfurters containing menhaden mince or surimi had very low levels of nitrosodimethylamine (Pensebene and Fiddler, 1988).

Bischoff (1986) reported on a well accepted "sea dog" frankfurter containing 50% surimi plus turkey and vegetable oil. Menhaden surimi or mince, despite its darker color would be suitable for this type of food application. Other emulsified meat products, such as a sandwich loaf or breaded nuggets, are also potential food applications.

Nonfood Specialty Products

Menhaden are an important bait species for fishermen, and they have been used in canned pet foods and in a variety of industrial products over the years. In addition to feeds, menhaden proteins or oil have been used in paints, plastics, cosmetics, and fertilizers (Lanier, 1985). Aquaculture feeds represent a growing market for fish meal. Additional applications of higher value suggested by research studies include: 1) A menhaden hydrolysate for possible use as a milk replacer for calf feeding (Hale and Bauersfeld, 1978); 2) the use of menhaden hydrolysates as fish peptones for the culture of microorganisms (Green et al., 1973); 3) use of menhaden as an ingredient in intermediate-moisture pet foods (Rasekh et al., 1976); and 4) the use of diluted menhaden solubles as an emulsion fertilizer for house plants and agricultural crops (Aung et al., 1984). These potential applications show some promise, but none are likely to have an impact on the menhaden industry.

Protein Products in New Forms

Menhaden Surimi

During recent years most American consumers have become familiar with surimi-based analog products, primarily in the form of imitation crab legs. An excellent description of processing methods for surimi and analog products was published by Lee (1984). During 1976-86, U.S. imports of surimi rose from about 1 million to 13.4 million pounds. Imports of surimi-based seafoods rose from 2.8 million to 61 million pounds. Most imports have now been displaced by domestic production, but U.S. consumption of surimi products was estimated at 135 million pounds in 1988 (Vondruska et al., 1989). Thus, the surimi market was seen as an opportunity for developing food products of higher value from menhaden.

Lanier et al. (1983) explored the use of menhaden for surimi production in both pilot and semi-commercial trials. Surimi prepared from Atlantic menhaden had excellent gel-strength when cooked in a 2-stage process at 40°C followed by 90°C. Surimi prepared from Gulf menhaden was lighter in color, but had a higher fat content and a lower gel-strength than the comparable Atlantic menhaden surimi.

The processing requirements for the preparation of minced intermediates or surimi from menhaden were also discussed by Regier et al. (1985). Extended menhaden holding studies in refrigerated seawater, chilled seawater, or on ice indicated that any of the methods are effective providing the fish are chilled rapidly after harvest. Processing procedures and yields were also described for both Atlantic and Gulf menhaden (Fig. 2, 3).

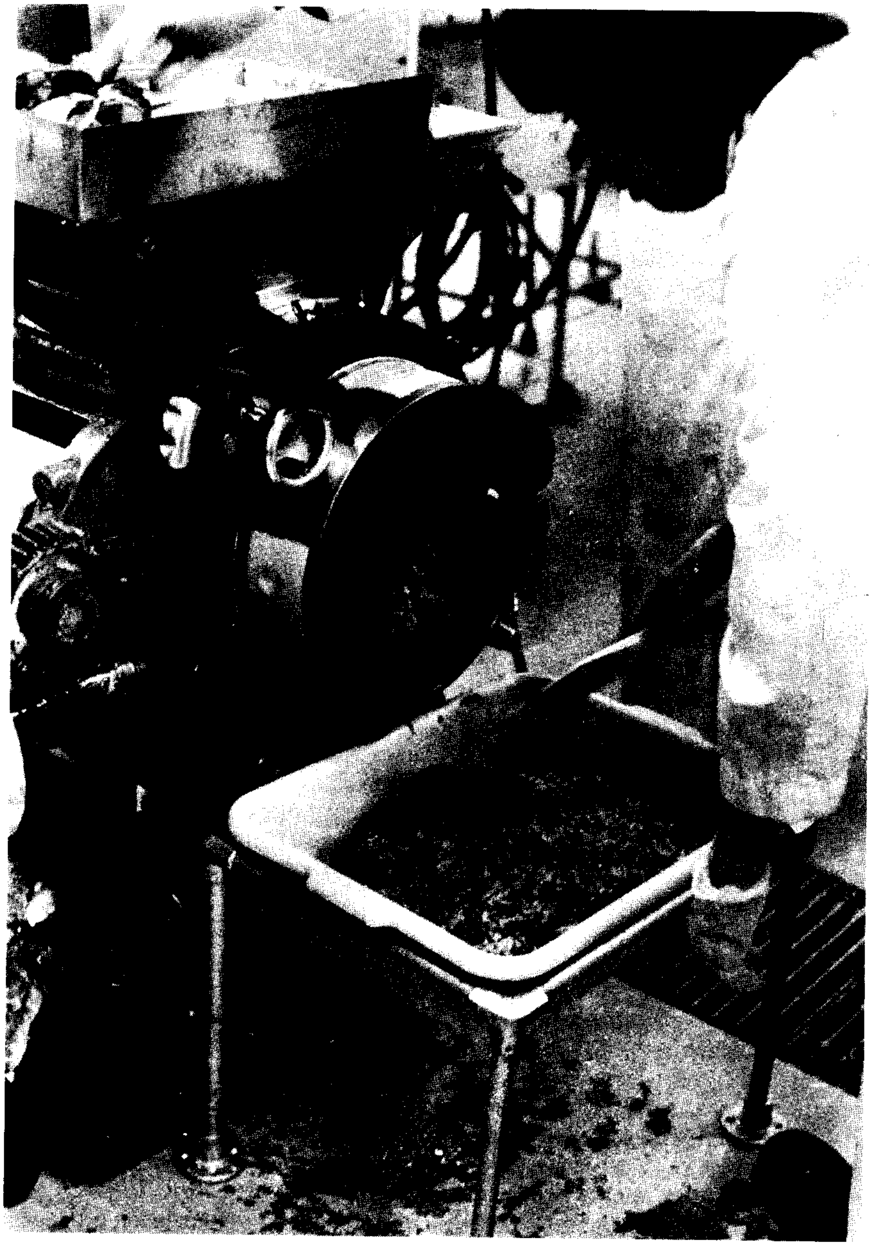

Figure 2.—Menhaden mince is prepared by mechanical separation of bones and skin.

Demonstration Plant

In 1985, the U.S. Congress designated increased funding for research and development into the conversion of menhaden into surimi. In 1986 an R&D contract for a 2-year, $2 million project was awarded to Zapata Haynie Corporation[1]. About $1.3 million in government funds was included. A pilot demonstration plant capable of producing one ton of surimi per day was constructed

[1]Mention of trade names or commercial products does not imply endorsement by the National Marine Fisheries Service, NOAA.

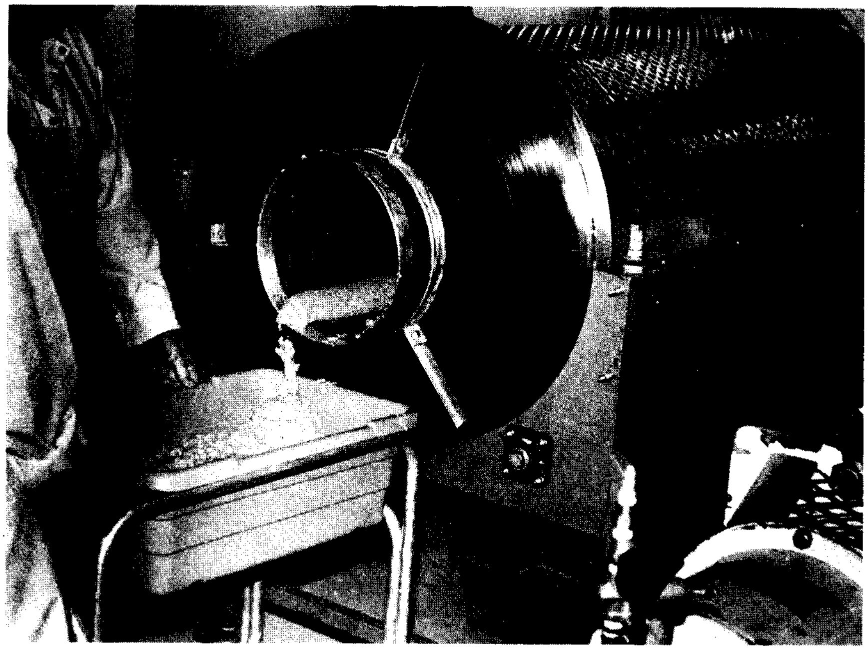

Figure 3.—Washed mince is partially dewatered with a rotary screen in the surimi process.

by Zapata Haynie adjacent to their meal and oil plant in Reedville, Va. The plant and the menhaden surimi processing operations carried out during the 1987 and 1988 fishing seasons have been described by Bimbo (1988b). Menhaden surimi was made available to researchers and manufacturers to investigate product applications. A production plant trial showed that the menhaden surimi had the functionality required for machine processing into analog products. Crab analogs were produced which were quite acceptable despite a somewhat darker color than the normal commercial product.

The following conclusions were made in the final contract report (Zapata Haynie, 1989):

1) Menhaden will produce a functional surimi with good gel properties, but with a gray color and slight residual flavor.

2) Economic feasibility is projected for a plant with a capacity of 22 tons of surimi per day.

3) The continuous wash with centrifugal separation gave a better yield and product quality in addition to being more labor efficient than the batch washing process.

4) Rapid chilling of the fish at harvest is essential for a quality surimi product.

5) Menhaden should be marketed in food products capitalizing on high protein, low fat properties and not as a white fleshed seafood analog ingredient.

Additional New Products

Fish purees, as defined by Miller et al. (1986), are pre-cooked before mechanical deboning or mincing and most of the fat is retained in the product. Such a product has nutritional advantages over surimi, from which fat and soluble protein have been washed out. Purees can be blended with a variety of food products as a source of beneficial omega-3 fatty acids. Miller has done extensive product development work with purees prepared from menhaden and from a number of popular food fishes.

The functionality of menhaden surimi for analog production has been demonstrated, but the darker color is a problem with most current analog shellfish product forms. Color would be less of a problem in a product that combined the surimi with machine-separated blue crab meat. There are other potential products such as breaded oyster analogs that would be compatible with the darker color. Fast food products have been studied at Virginia Polytechnic Institute, and researchers at the University of Georgia have incorporated menhaden surimi into a very acceptable pasta product (Bimbo, 1988b).

Menhaden was a primary species for fish protein concentrate (FPC) investigations in the late 1960's (Dubrow et al., 1976). The economics of FPC were not favorable, but a new dry fish protein product called Marinbeef is currently produced and marketed by the Japanese. The processing and properties of Marinbeef have been described by Suzuki (1981). It is functional, can be reconstituted to a hamburger-like consistency, and represents another potential product application for menhaden.

Oil-based Products

World production of marine oils totals about 1.5 million metric tons (t) (Bimbo, 1989). Marine oils account for a little over 2 percent of the world production of fats and oils. Menhaden oil production was 0.10 million t in 1989, valued at $23.2 million (NMFS, 1990). Menhaden oil accounted for 97 percent of the total U.S. fish oil production. The volume of menhaden oil produced each year fluctuates because of natural variations in both the abundance of stocks and the oil content of menhaden. For the 10-year period of 1980-89, the average annual menhaden oil production was 0.132 million t.

Use of Menhaden Oil

Most of the fish oil produced in the United States is exported to western Europe. There the oil is partially hydrogenated for use in margarines and shortenings. Except for the United States, all countries producing marine oils utilize them in foods. In the United States, fish oils are being consumed in only two forms: 1) Imported fish oils are being marketed in capsules as food supplements and 2) small quantities of fish oils are being consumed as canning oils. However, this was not always the case. Before the disappearance of the California sardine in the early 1950's, large amounts of hydrogenated fish oils were consumed in margarines and shortenings in this country. During the peak years of usage, 1930-40, U.S. fish oil consumption for all edible purposes was 68,000 t per year. Menhaden oil was never included on the GRAS (Generally Regarded as Safe) list, and in 1955, when the standard of identity for oleomargarine was established by the U.S. Food and Drug Administration (FDA), fish oil availability had diminished and no one requested that fish oils be included on the list of acceptable ingredients (Bimbo, 1989). Thus, for menhaden oil to be included in margarine two legal actions must be taken: 1) GRAS status must be established and 2) the standard of identity must be amended.

Oil has always been an important product of the menhaden industry. Prior to World War II, menhaden oil was used in the manufacture of a variety of industrial products. However, technological advances eventually led to the exclusion of fish oils in many of these products. Most menhaden oil is now exported for food use. The functional properties and low cost of the oil make it attractive for such uses. Because of its special properties, some menhaden oil is still sold in the United States for certain industrial applications. Some of the products containing menhaden oil include protective coatings, lubricants, printing inks, carriers of insecticides, caulks and sealants, surfactants, plasticizers, and leather treatment agents. Fish oil fatty acids are raw materials in the production of a wide range of chemical derivatives. Menhaden oil is also utilized as an important nutrient in the diets of poultry, livestock, and fish, both in the form of oil and as a component of menhaden fish meal. Because of the current nutritional interest in omega-3 fatty acids, for which menhaden oil is a major source, animal scientists are exploring avenues by which these fatty acids can be incorporated into the meats we eat.

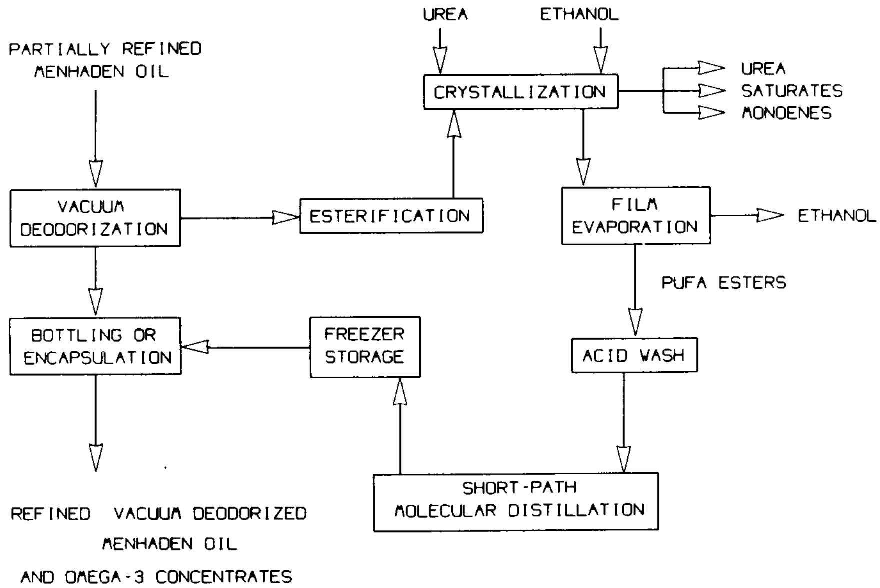

Figure 4.—Basic process for the preparation of biomedical test materials from partially refined menhaden oil at the NMFS Charleston Laboratory.

Biomedical Test Materials

Appreciation of the unique and important contribution of seafood lipids (oils) to human health really began with the publication of a series of Danish studies on the low incidence of heart disease in Greenland Eskimos. A number of subsequent studies in this and other countries led to the hypothesis that increased consumption of seafoods or fish oils rich in omega-3 polyunsaturated fatty acids (PUFA) can have direct and positive influence in preventing or ameliorating many degenerative disease processes (Lands, 1987; Kinsella, 1986). At a conference held in 1985 entitled "Health Effects of Polyunsaturated Fatty Acids in Seafoods," leading researchers in this area concluded that a significant limitation in the research was the lack of adequate supplies of quality-assured test materials of consistent composition to explore the many research frontiers identified by the conferees (Simopoulos, et al., 1986). Under a 1986 Memorandum of Understanding (MOU) between NOAA and the National Institutes of Health (NIH), it was agreed that the NMFS Charleston Laboratory would provide a long-term consistent supply of test materials, derived from menhaden oil, to facilitate evaluation of the role of omega-3 fatty acids in health and disease. An interagency committee in the Division of Nutrition Research Coordination of NIH, the Fish Oil Test Materials Advisory Committee (FOTMAC), provides the review and approval mechanism for the distribution of quality-assured/quality-controlled test materials to researchers. The applicants are investigators who are funded by NIH or other research organizations.

Production and Quality Control

The production facility at the Charleston Laboratory includes equipment for preparation of biomedical test materials from partially refined menhaden oil as outlined in Figure 4. Also available for fractionation of concentrates are a process-scale high performance liquid chromatograph (HPLC) and supercritical fluid CO_2 fractionator (SCFF). Test materials are produced by a number of physical and chemical separation techniques. Menhaden oil, which has undergone winterization, alkali refining, and bleaching by the supplier, is passed through a wiped film deodorizer to reduce cholesterol, organic contaminants, and fishy odors and flavors to very low or undetectable levels. The antioxidant TBHQ and vitamin E in the form of alpha- and gamma-tocopherol, are added to the product receiver. The yield of deodorized oil is about 75 kg per 8-hour day. A portion of this oil is reserved as a test material; the balance is used to produce omega-3 concentrates.

To produce a test material containing at least 75 percent omega-3 polyunsaturates, the menhaden triglycerides are transesterified to produce fatty acid ethyl esters. The esters are reacted with urea dissolved in hot ethanol and the solution is cooled overnight. Upon cooling, the straight chained saturated and monounsaturated esters form adducts with urea which precipitate from the alcoholic solution, thereby concentrating the nonadducted polyunsaturated esters. After the ethanol is stripped from the solution in a film evaporator, the neat esters are distilled in a wiped film molecular still to remove oxidation products, polymers, color bodies, and additional cholesterol. An initial charge of 80 kg esters yields about 12 kg of purified omega-3 concentrates. Purified eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3) are also produced, with portions of the omega-3 concentrates serving as feed stock. Either HPLC or SCFF, or a combination of the two procedures, are used to produce the purified fatty acid esters.

Refined fish oil containing protective antioxidants is available in bulk or in soft-gelatin capsules; refined oil without antioxidants is available in bulk upon special request. In addition, soft-gelatin encapsulated food grade vegetable oils (corn, olive, and safflower) are available for use as placebos. Because of the instability of the omega-3 ethyl ester concentrates, they are provided only with antioxidants but may be obtained either in bulk or in soft-gelatin capsules; encapsulated ethyl esters of corn, olive, and safflower oils are produced for use as placebos. Purified EPA and DHA are available only in bulk and in small quantities and contain no antioxidants.

Production of the test materials is monitored by a series of quality control chemical analyses whose results demonstrate that proper procedures were used during each phase of production. The most important analyses include: High performance gas-liquid chromatography for organic contaminants (PCB's and pesticides), sterols, antioxidants, and fatty acid composition; measurement of peroxide value to detect signs of oxidation; and sensory evaluation of odor and flavor by a trained sensory panel. Test materials undergo additional quality assurance analyses including trace metals, macroelements, oxidation products, and microbiological tests before shipment to approved investigators.

Second International Conference

A Second International Conference on the "Health Effects of Omega-3 Polyunsaturated Fatty Acids in Seafoods" was held in Washington, D.C., in March 1990. The conference of distinguished investigators, from around the world, critically reviewed research data collected during the past 5 years.

About 40 invited papers were presented. Session topics included information on the relationship of omega-3 fatty acids to growth and development, advances in mechanisms of action, heart disease and hypertension, rheumatoid arthritis and inflammatory mediators, diabetes, psoriasis, and cancer. Over 80 posters were presented representing researchers from about 20 countries around the world. Several significant conclusions were drawn during the conference. The essentiality of omega-3 fatty acids was firmly established, and the role of DHA was clearly defined in the field of human growth and development. The necessity for the inclusion of this important fatty acid in infant formulas was mandated, and the practice of long-term feeding with formulas that do not include the omega-3 fatty acids was questioned. The role of the omega-3 fatty acids in prevention or treatment of several disease states was clearly confirmed. Significant advances were made in the understanding of the biochemical mechanisms of action in the areas of cardiovascular disease, inflammation, and cancer.

A milestone of the meeting was the establishment of the Society for Fatty Acids and Lipids. The Society held its charter meeting at the end of the conference. Another milestone of the meeting was the presentation of data that demonstrated that as little as three meals of fish per week, coupled with a decrease in total fat intake, provides striking protection against mortality from cardiovascular disease.

FDA Petition

It is ironic that there is such interest in increasing the amount of omega-3's in the foods we eat, yet refined menhaden oil lacks FDA's approval for food use. In June 1986, the National Fish Meal & Oil Association submitted a GRAS petition to the FDA for both refined menhaden oil (RMO) and partially hydrogenated menhaden oil (PHMO). In September 1989, the FDA extended GRAS status to hydrogenated and partially hydrogenated menhaden oils, but delayed a decision on RMO. The results of a study contracted by FDA were reported by the Mitre Corporation in February 1989. The Mitre Report found no serious problems with the safety of refined menhaden oil (Bimbo, 1989). A decision on GRAS status for RMO, with its content of beneficial omega-3 fatty acids, is awaited by industry and consumers.

Potential Uses

Partially hydrogenated menhaden oils may be blended into shortenings and margarines subject to FDA approval and amendment of the standard of identity for margarine. The use of refined menhaden oil with the omega-3 fatty acids preserved, however, could have a more significant impact on consumer products. Since the hydrogenation process destroys omega-3 fatty acids, the oil constituents purported to have important biological effects, the challenge to the food industry is to develop new products in which the omega-3 fatty acids are protected. In addition to the potential uses as a canning oil, menhaden oil could be used in mayonnaise and salad dressings if properly protected from oxidation by antioxidants and special packaging. An Institute of Food Technologists (IFT) Short Course on Seafood Technology in June 1988 included some information on current research into the preparation of such food products incorporating refined fish oils (Bimbo, 1988a). Work conducted in Europe, under the sponsorship of the International Association of Fish Meal Manufacturers, included evaluations of pastes and spreads, mayonnaise, salad oils, yogurt, canned fish, and several types of sausages. Fish oils were blended in differing proportions with other oils or fats into the products. Some flavor problems were encountered, but many products with significant fish oil content were fully acceptable.

The production and evaluation of margarines containing refined, unhydrogenated fish oil were recently reported by Young et al. (1990). The quality and shelflife of margarines containing refined fish oil (at 20% of the fat content) were tested with three different packaging methods and two different antioxidants. The results showed that the experimental margarine containing fish oil had a refrigerated shelflife of at least 10 weeks and the quality was similar to that of the all-vegetable oil control margarine. The results also indicate a way in which refined menhaden oil could enjoy a higher valued use and provide beneficial amounts of omega-3 fatty acids to consumers.

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Assessment and Management of Atlantic and Gulf Menhaden Stocks

D. S. VAUGHAN and J. V. MERRINER

Introduction

Stock assessment refers to the process of collecting and analyzing biological and statistical information to determine changes in abundance of fish stocks in response to fishing, and, to the extent possible, predict future trends of stock abundance. Relevant questions arising during such an assessment include:

1) Do current landings exceed maximum sustainable yield or some other measure of optimal yield?
2) Is recruitment sufficient to support current levels of landings?
3) Does recruitment depend more on spawning stock size or more on environmental conditions?
4) Should age-at-entry to the fishery (minimum size or age landed) be raised to increase yield to the fishery?

Fishery management, or the system used to conserve and allocate fishery resources, must address these questions.

Two "overfishing" concepts are referred to in this paper. The concept of "growth overfishing" refers to the trade-off between catching greater numbers of younger and smaller fish or catching fewer numbers of older and larger fish. The trade-off depends both on the rate of growth of individual fish and on their natural mortality rate. The concept of "recruitment overfishing," on the other hand, refers to a concern that insufficient numbers of fish are reaching spawning age and subsequently reducing the number of future recruits below levels that will maintain the stock at fishable levels.

Landings and fishing effort data have been collected for the Atlantic menhaden purse-seine fishery since 1940 and for the Gulf menhaden purse-seine fishery since 1946 (Smith, 1991). Port sampling data for size and age composition from scales (procedures described by Chester, 1984) have been conducted by NMFS port samplers since 1955 for the Atlantic menhaden purse-seine reduction fishery and since 1964 for the Gulf menhaden purse-seine reduction fishery.

This paper describes the organization of coastwide management programs for the Atlantic and Gulf menhaden stocks, summarizes current information about the effects of purse-seine fishing for reduction on these stocks, and discusses management implications drawn from this information. Regular stock assessments are conducted on Atlantic and Gulf menhaden and have been presented at stock assessment workshops held by the NMFS Southeast Fisheries Science Center (Powers, 1983; Vaughan et al., 1986). Estimates of age-specific population numbers and fishing mortality rates, spawning stock, and recruits to age-1 are obtained from virtual population analysis (VPA) conducted separately for both Atlantic and Gulf menhaden. Equilibrium spawning stock ratios are computed to compare the level of spawning stock expected based on estimated fishing mortality for a fishing year to that level with no fishing mortality. Estimates of potential yield from varying age at entry to the fishery and fishing mortality rates are investigated using yield-per-recruit analysis. Recent landings are compared to estimates of maximum sustainable yield (MSY) obtained from surplus production, spawner-recruit, and population simulation models. Finally, management implications drawn from this information are discussed in light of the past decade of management actions and inactions by the coastal states.

Organization of Coastwide Management Programs

Authority for menhaden fishery management resides with individual states. The formation of the Atlantic and Gulf States Marine Fisheries Commissions (ASMFC and GSMFC, respectively) in the 1940's provided a forum for discussion and resolution of common marine resource issues and a vehicle for development of cooperative multistate fisheries programs such as for menhaden. The NMFS serves as the primary research agency dealing with menhaden for the commissions. Through the years this state-federal research and fishery management system drew heavily upon input and voluntary participation of the menhaden industry. This informal institutional arrangement provided guidance and fishery oversight through the 1960's and into the 1970's. Interstate research and monitoring coordination was through the ASMFC Advisory Com-

ABSTRACT—The organization of coastwide management programs for Atlantic menhaden, Brevoortia tyrannus, *and Gulf menhaden,* B. patronus, *are described. Recent assessments of the status of the Atlantic and Gulf menhaden stocks are summarized. Estimates of population size and fishing mortalities are obtained from virtual population analysis, and are used in determining spawner-recruit relationships, spawning stock ratios, yield-per-recruit, and surplus production. Management issues are addressed in the framework of assessment results.*

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mittee and the GSMFC Technical Coordinating Committee (TCC).

Atlantic Menhaden

Development of an Atlantic Menhaden Management Plan under the auspices of the ASMFC and the State-Federal Fisheries Management Program was begun by the Statistical and Scientific Committee (SSC) in fall 1976. The SSC had a very general charge and prepared an interim report (plan) in February 1977. In July 1977 the SSC was asked to prepare a plan for the utilization of Atlantic menhaden that "is biologically, economically, and socially sound and which protects the resource and its users" (AMMB, 1981). Over the next 3 years the SSC and Atlantic Menhaden Management Board (AMMB) developed a plan, with supporting analyses by staff of the NMFS Beaufort Laboratory. In 1981 the AMMB, and later that year the full ASMFC, adopted the menhaden plan (AMMB, 1981). This plan recommended adjustment of time and area closures if necessary (based upon the best data available) to achieve a short-term objective of attaining an age composition in the population which included 10% age-3 or older and established an organizational framework for management. The contents of the plan and the management structure were a combined state, industry, and Federal effort of data gathering, analysis, and fishery management decision-making. Later, fishery statistical information in the fishery management plan was updated (AMMB, 1986).

In May 1982 the AMMB considered several management options which would reduce pressure on age-0 and age-1 fish and increase yield-per-recruit: Season options, closed corridor, and mesh size. The AMMB approved a variable seasonal closure by geographic area (also known as option 7) which reduced the duration of fishing activity by 4 weeks in each of four geographic areas (AMAC, 1982). Recent analyses have been conducted comparing the shortened season option to the closed corridor option (Blomo, 1987; Vaughan and Smith, 1991). That recommendation has yet to be implemented in all coastal states having an active purse-seine fishery, most notably North Carolina.

For various reasons, several states recently have passed severe limits on menhaden purse-seine fishing (New Jersey, Delaware, and South Carolina have closed all or part of their waters). Continued human population growth in the Atlantic coastal zone and conditions in the U.S. economy have resulted in pressures for fishery restrictions based on political reasons rather than the biological needs of the fishery resource as called for in the plan. This is tending toward a reduced number of operating plants and reduced fleet size in the Atlantic menhaden fishery (Smith, 1991). By 1988 reduction plants for Atlantic menhaden were reduced to four U.S. shore-based facilities (one in Maine, two in Virginia, and one in North Carolina). The 1989 fishing year was the third during which menhaden caught off Maine were transported to a land-based facility in New Brunswick, Can., for reduction, and the second year of an Internal Waters Processing venture between a Maine company and the Soviet Union; Maine fisherman caught Atlantic menhaden and offloaded the fish onto a Soviet processing vessel (F/V *Riga*). The land-based reduction plant in Maine ceased operation following the 1988 fishing year.

Furthermore, in 1987 the ASMFC in its Interstate Fishery Management Program reorganized the management structure for territorial sea fish species. That action eliminated the AMMB and AMAC; it also removed most of the industry's participation in the management process. The new plan review procedure calls for annual status reports on the fishery and resource to be done by the ASMFC Advisory Committee or a designated special plan review subcommittee (which for menhaden consisted of the former membership of AMAC).

As a result of the changes in ISMFP structure and in the reduction fishery, the ASMFC reconstituted the Atlantic Menhaden Management Board in 1988 with three state members (Maine, Virginia, and North Carolina). Two industry members were added to the Board in 1990. The Atlantic Menhaden Advisory Committee also was reconstituted to maintain the vital mix of state, industry, and Federal representation and serve as a clearinghouse for proposed regulations or laws affecting the menhaden fishery. Preparation of a major rewrite of the Fishery Management Plan by the Atlantic Menhaden Advisory Committee began in 1989 with expected completion in 1992.

Gulf Menhaden

The Gulf Menhaden Regional Fishery Management Plan (Christmas and Etzold, 1977) was developed in the 1970's as a product of the Gulf Menhaden Subcommittee of the TCC; it was composed of state, industry, and Federal representatives. The charge to the subcommittee was to consider the need for and possible procedures for establishing a uniform menhaden fishing season in the Gulf Coast states. In spring 1976 the Menhaden Subcommittee, the TCC, and the Gulf State-Federal Fishery Management Board endorsed a proposal to develop a fishery management plan for Gulf menhaden. With support of NMFS, the states, and industry, the plan was developed and issued in May 1977 (Christmas and Etzold, 1977). Revisions of the plan have been issued by the GSMFC in about 5-year intervals (Christmas et al., 1983, 1988), providing updates of stock assessments of the resource, descriptions of industry, fishery, biology, and identification and ranking of research needs. The major management feature of the Gulf menhaden plan is a uniform season (third Monday of April through the Friday following the second Tuesday in October, equals 26 weeks) adopted by all Gulf of Mexico states, with the exception of Florida, and a formal organizational structure for interjurisdictional management. Individual Gulf coast states vary in other measures (such as licenses, sanctuaries, and penalties) enforced upon the menhaden fishery. The program has been very effective and GMAC continues to meet biannually to review stock status and management measures.

Atlantic Menhaden

Summary of Recent Stock Assessments

Growth overfishing has been of pri-

Table 1.—Annual estimates of Atlantic menhaden population size (age 1-8 at start of fishing year) and numbers landed (age 1 to maximum age observed), exploitation rates (u, age 1-8), and weighted mean F (1/year), for fishing years, 1955-87.

Fishing year	Population size in billions	Numbers landed in billions	u	F
1955	6.97	2.36	0.339	0.501
1956	8.30	3.53	0.425	0.825
1957	9.83	3.21	0.327	0.819
1958	7.12	2.61	0.367	0.666
1959	17.63	5.34	0.303	0.552
1960	9.31	2.70	0.290	0.491
1961	6.84	2.60	0.380	0.706
1962	4.59	2.05	0.447	1.162
1963	3.60	1.67	0.464	1.092
1964	2.77	1.43	0.516	1.013
1965	2.59	1.26	0.486	1.040
1966	2.07	0.99	0.478	0.758
1967	2.50	0.98	0.392	0.787
1968	2.02	0.99	0.490	1.211
1969	2.22	0.71	0.320	0.676
1970	3.44	1.38	0.401	0.778
1971	2.46	0.90	0.366	0.807
1972	4.32	1.66	0.384	1.140
1973	4.18	1.79	0.428	1.755
1974	4.33	1.68	0.388	1.302
1975	5.24	1.86	0.355	1.235
1976	8.74	3.01	0.344	0.975
1977	8.40	3.19	0.380	1.011
1978	7.62	2.63	0.345	1.041
1979	7.08	2.38	0.336	0.728
1980	9.35	3.24	0.347	0.925
1981	8.15	2.80	0.344	0.763
1982	9.42	3.06	0.325	1.224
1983	6.15	2.98	0.485	1.082
1984	5.48	2.25	0.411	0.888
1985	6.85	2.39	0.349	0.990
1986	7.26	1.82	0.251	1.152
1987	8.19	2.37	0.289	0.902

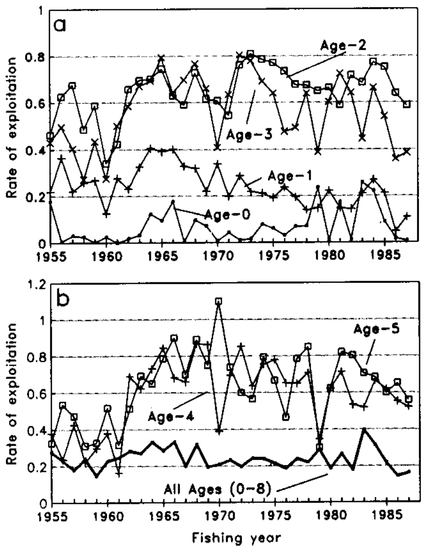

Figure 1.—Estimates of annual rates of exploitation of Atlantic menhaden (ages 0 through 5 and total population (ages 0-8)), for fishing years 1955-87.

mary concern with the Atlantic menhaden stock. Information presented in this section is drawn primarily from Ahrenholz et al. (1987), Vaughan and Smith (1988), and some recent analytical results prepared for AMAC. The Atlantic menhaden fishery is believed to exploit a single stock or population of fish based on tagging studies (Dryfoos et al., 1973; Nicholson, 1978a). The Atlantic menhaden fishing season runs from March 1 through the end of February of the following calendar year for the reduction fishery.

Population size (age-1 and older at the start of the fishing season) ranged from 2.0 billion Atlantic menhaden in 1968 to 17.6 billion fish in 1959 (Table 1). Population size averaged 9.2 billion menhaden between 1955 and 1961 when landings were high (averaging 604,000 t), and averaged 3.2 billion menhaden between 1962 and 1974 when landings were low (averaging 289,000 t). However, since 1975 population size has averaged 7.5 billion menhaden, comparing favorably to population sizes between 1955 and 1961, but landings have improved only slightly to an average of 341,000 t. The inability of the modern fishery to regain former high levels of landings is due primarily to declining mean weight at age occurring since 1970 (Reish et al., 1985; Ahrenholz et al., 1987; Vaughan and Smith, 1988), caused in part by changes in fishing patterns both geographically and seasonally. Part of this decline is due to the shift of the center of the fishing activity southward and subsequent seining on smaller fish at age and part can also be explained by the inverse relationship noted between first year growth of Atlantic menhaden and year class strength (Reish et al., 1985; Ahrenholz et al., 1987).

Short-term losses to the Atlantic menhaden stock due to the fishery can be assessed by considering the exploitation rate (Fig. 1), which is the fraction of the remaining stock removed by the fishery during some specified period of time (usually 1 year). Population exploitation rates (based on age-1 and older Atlantic menhaden) averaged 38% of the population removed by fishing for 1955 through 1987 (Table 1). From 1955 through 1961 when population size and landings were high, population exploitation rate averaged 35%. During the period of low population size and landings from 1962 through 1974, population exploitation rate averaged 43% (initially high during the mid-1960's and lower during the late 1960's and early 1970's). Since 1975 when population size and landings have improved significantly, the population exploitation rate has averaged 35%. For fishing years 1955 through 1987, an average of 24% of age-1 menhaden and 65% of age-2 and older menhaden were taken by the fishery annually, with 30% and 20%, respectively, being lost to natural causes annually (compared to 36% lost to natural causes annually in the absence of fishing mortality). Age-specific exploitation rates for age-0 menhaden range from essentially 0% to 26%.

The number of Atlantic menhaden spawners (age 3 and older at the start of the fishing year) ranged between 0.03 billion in 1973 and 1.3 billion in 1961 (Table 2). High spawning stock size (averaging 0.6 billion menhaden) was the rule between 1955 and 1961, low spawning stock size predominated between 1962 and 1974 (averaging 0.1 billion menhaden), and some improvement in spawning stock size has occurred since 1975 (averaging 0.2 billion menhaden). Between 1955 and 1961 high spawning stock size resulted in excellent recruitment of age-1 menhaden (averaging 5.5 billion) entering the fishable stock. Low spawning stock size present from 1962 through 1974 produced poor recruitment (averaging 2.2 billion menhaden). However, the somewhat improved spawning stock size present since 1975 has produced excellent recruitment (averaging 5.0 billion menhaden), comparable to that produced during the high spawning stock years (1955-61).

Since 1955 the contribution of late age-2 spawners to the spawning stock has averaged about 76% in numbers and 66% in index of egg production (Fig. 2).

Table 2.—Estimated number of spawning Atlantic menhaden (age 3-8 females) that produced the year class, estimated egg production from the spawning stock, and estimated numbers of recruits to age-1 by year class, 1955-86.

Year class	Spawners: Number in billions	Spawners: Number of eggs in trillions	Number of recruits to age-1 in billions
1955	0.795	152.6	5.68
1956	0.587	124.1	7.25
1957	0.282	65.9	3.32
1958	0.216	42.5	15.10
1959	0.538	77.2	2.22
1960	0.307	57.5	3.01
1961	1.321	152.9	2.23
1962	0.545	91.1	2.23
1963	0.176	30.3	1.74
1964	0.084	14.1	1.91
1965	0.059	9.3	1.37
1966	0.028	4.0	1.93
1967	0.056	9.4	1.18
1968	0.050	7.4	1.68
1969	0.039	6.3	2.57
1970	0.045	7.3	1.33
1971	0.084	12.6	3.44
1972	0.120	22.1	2.69
1973	0.031	5.9	2.99
1974	0.038	5.3	3.75
1975	0.044	5.9	6.80
1976	0.057	6.6	5.12
1977	0.099	10.7	4.69
1978	0.226	18.1	4.21
1979	0.199	16.3	6.65
1980	0.253	23.8	4.67
1981	0.198	17.5	6.36
1982	0.316	19.6	2.45
1983	0.178	14.4	3.81
1984	0.254	22.4	5.07
1985	0.076	8.1	4.70
1986	0.083	7.2	4.95

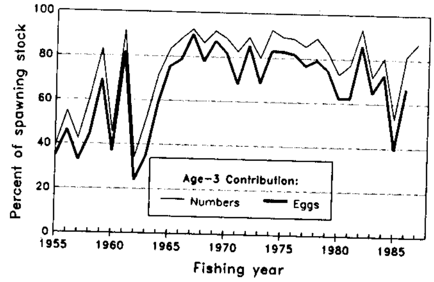

Figure 2.—Contribution of age-3 spawners to total spawning stock (numbers) and to total egg production (eggs) of Atlantic menhaden for fishing years 1955-87.

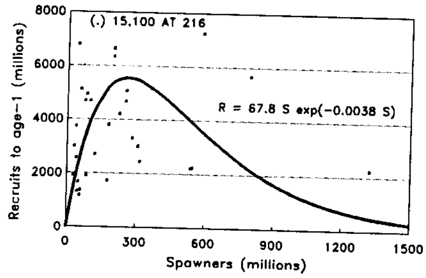

Figure 3.—Numbers of Atlantic menhaden recruits (R) plotted against numbers of spawners (S) for year classes, 1955-86. Curve represents the fitted Ricker function $R = \alpha S \exp(-\beta S)$.

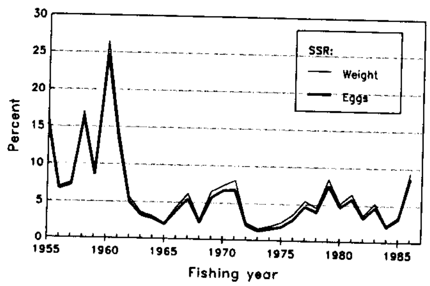

Figure 4.—Equilibrium spawning stock ratio in weight and index of egg production for Atlantic menhaden for fishing years, 1955-86.

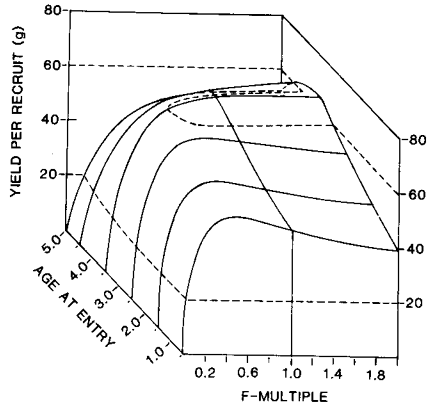

Figure 5.—Yield-per-recruit isopleth diagram for Atlantic menhaden using average growth and fishing mortality values by quarter for the 1981 fishing year.

These values were exceptionally high during the 1970's (87% and 78%, respectively), but have declined somewhat during the 1980's (77% and 65%, respectively), lessening the concern that recruitment failure in a single year class could have significant consequences on future year classes. When spawner and recruit data are fit to the Ricker model (Ricker, 1975), a statistically significant relationship is obtained (Fig. 3). However, considerable unexplained variability about the estimated spawner-recruit curve suggests that recruitment variability depends little on spawning stock size, and that environmental factors are probably more important in controlling recruitment success or failure.

Gabriel et al. (1984) suggested that a ratio of spawning stock size calculated when fishing mortality is equal to that estimated for the present divided by the spawning stock size calculated when F is equal to 0 (unfished stock). This ratio does not consider such compensatory mechanisms as increased growth rate or earlier maturity when a fish stock is reduced from fishing. It was thought that this ratio would provide values below which it should not be allowed to decline to protect the stock from recruitment overfishing. These ratios, as presented here, are calculated under the assumption of equilibrium; that is, annual age-specific estimates of F are used to project a fixed number of recruits throughout their lifespan and sum the spawning stock in weight or index of egg production. The index of egg production for Atlantic menhaden is based on the egg-length relation provided in Lewis et al. (1987).

Since 1962 the spawning stock ratio has remained below 10% (Fig. 4). Because values of 20%-40% have been used by the Gulf of Mexico and South Atlantic Fishery Management Councils in their definitions of overfishing for a number of fish stocks, these low values for Atlantic menhaden raise concern. However, periods of both poor recruitment and excellent recruitment have occurred since 1962, reinforcing the concept that environmental conditions are most important in determining recruitment success.

Yield-per-recruit models are used to determine whether Atlantic menhaden are being removed at too young an age (growth overfishing). A yield-per-recruit isopleth shows gains and losses of yield-per-recruit as a function of fishing mortality rate or age at entry to the fishery (Fig. 5). Overall yield-per-recruit for the age at entry of 0.5 year and F-multiple of 1.0 has been decreasing since 1971 with an average of 58.7 g for the period 1970-84 (Table 3). The proportional contribution of younger age groups to the landings has been increasing, and the average size at age (as noted earlier) is decreasing. Reduced growth and redirection of effort toward younger fish are contributing to the reduced levels in yield-per-recruit.

Recent landings of Atlantic menhaden have been increasingly dependent on age-0 menhaden (e.g., 1979, 1981, 1983, 1984, and 1985 as noted in Vaughan and Smith, 1988). Gain in yield-per-recruit from increasing age-at-entry to age-1 would have ranged from 0.7% in 1970 to 11.1% in 1979 and 8.7% in 1981. Even greater gain in yield-per-recruit could be obtained by raising the age-at-entry to age-2 (17.0% in 1979 and 12.9% in 1981). However, management options that protect only age-0 (or age-1) menhaden have been difficult to devise (Vaughan and Smith, 1991).

Historical estimates of maximum sustainable yield (MSY) range from 370,000 to 560,000 t (Schaaf and Huntsman, 1972; Schaaf, 1975, 1979; Ahrenholz et al., 1987; Vaughan and Smith, 1988). The most recent application of surplus production models conducted for AMAC, which relate landings and fishing effort, suggest estimates of MSY of 484,000 t ($\pm$87,000 t) based on landings and adjusted fishing effort data through 1986. High recruitment from 1975-1981 indicates potential yields of 416,000 to 481,000 t based on yield-per-recruit analysis. In general, estimates of MSY exceed recent landings of Atlantic menhaden which range from 238,000 to 418,600 t since 1980 with landings in 1989 at about 322,000 t.

Management Implications

Although landings have recovered somewhat from the depressed levels of the 1970's, they have not returned to the levels attained during the late 1950's when they averaged 625,000 t during the 1955-59 fishing years (Smith et al., 1987b). Recent estimates of MSY of 484,000 t $\pm$ 87,000 t at a mean F of 0.54/year were obtained from a generalized production model (1955-86); those levels are unlikely to be attained over an extended period given the present structure of the fishery. However, during the 1980's landings averaged 341,000 t with a mean F averaging 0.94/year suggesting greater landings would be available with less effort.

Table 3.—Estimates of yield-per-recruit (g) for Atlantic menhaden for each fishing year from 1970 through 1981, and for mean conditions for the period 1970-84. Estimates are presented for three ages at entry (0.5, 1.0, and 2.0 years) and three F-multiples (0.4, 1.0, and 1.6) (Vaughan and Smith, 1988).

Fishing year	Age at entry 0.5	1.0	2.0	F-multiple 0.4	1.0	1.6
1970	93.6	94.3	93.8	77.1	93.6	93.5
1971	107.5	108.8	118.0	97.9	107.5	104.6
1972	102.1	103.4	118.9	108.6	102.1	94.1
1973	92.2	93.3	101.7	96.5	92.2	86.5
1974	87.2	91.1	101.6	91.8	87.2	80.0
1975	78.6	80.5	86.8	83.4	78.6	73.4
1976	66.7	68.9	78.7	65.8	66.7	60.9
1977	54.4	57.5	63.5	59.5	54.4	48.7
1978	54.1	57.0	59.8	56.4	54.1	50.3
1979	53.0	58.9	62.0	48.9	53.0	49.2
1980	53.8	54.3	61.6	54.5	53.8	49.5
1981	45.9	49.9	51.8	51.1	45.9	41.3
			Mean conditions			
1970-84	58.7	60.6	64.4	57.3	58.7	55.7

Historical MSY estimates since the early 1970's have shown no trends, ranging between 370,000 and 570,000 t. Sufficient recruitment to attain MSY has been available since 1975, but with considerable variation about the fitted spawner-recruit curves (Fig. 3). It appears that managing the fishery to maintain large numbers of spawners may prove fruitless since environmental conditions appear to outweigh the availability of spawners (as numbers or eggs) in controlling subsequent recruitment. This is suggested by a poor, but statistically significant, spawner-recruit relation and high recruitment both following and concurrent with low spawning-stock ratio. However, the Ricker spawner-recruit relationships are marginally significant, and age-3 spawners are of great importance to the spawning stock (Fig. 2). Thus, further increasing the number of older (age-3 and older) spawners would guard against a possible stock collapse brought on by heavy fishing during a period of poor recruitment.

In general, increasing the age at entry causes an increase in the yield-per-recruit, except for small F-multiples; e.g., F-multiple = 0.2 (Table 3). On the other hand, decreasing the F-multiple to F-multiple = 0.6 generally causes a decrease in yield-per-recruit, except for the 1979 fishing year. Greater declines or any increases in the F-multiple generally causes a decrease in yield-per-recruit at the current age at entry. These results suggest that the fishery is harvesting the Atlantic menhaden stock at too young an age, and that the age at entry should be raised to increase potential yield from the stock.

In summary, the modern purse-seine fishery for the Atlantic menhaden has a high dependency on prespawners (age-2 and younger fish), so large fluctuations in year-to-year availability and catches are to be expected. To increase yield and enhance the stability of the resource, it is desirable that the number of age classes significantly contributing to the fishery be increased. The intent is to harvest more of the stock at an older age, while decreasing fishing mortality on the younger immature menhaden. This would create a buffer in the spawning stock against future years of poor recruitment and lessen the year-to-year fluctuations in landings by increasing the proportion of Atlantic menhaden that survive to spawning age. Furthermore, greater yields would be obtained from the stock. Whether landings near the MSY estimates of 450,000 to 490,000 t are attainable is questioned because of changes in plant locations and fishing patterns. However, gains in yield-per-recruit are possible by adjusting the age at entry to the fishery (Vaughan and Smith, 1991).

Gulf Menhaden

Summary of Recent Stock Assessments

Recruitment overfishing has been of primary concern with the Gulf menhaden stock. The summary of information presented in this section draws heavily on Nelson and Ahrenholz (1986) and Vaughan (1987). The Gulf menhaden fishery is also believed to exploit a single stock or population of fish based on tagging studies (Ahrenholz, 1981). The Gulf menhaden fishing season runs from

Table 4.—Annual estimates of Gulf menhaden population size (age 1-4 at start of fishing year) and numbers landed (ages 1-4), population exploitation rate (u), and population F (1/year), for fishing years, 1964-83 (Vaughan, 1987).

Fishing year	Population size in billions	Numbers landed in billions	Population u	Population F
1964	11.32	4.95	0.437	1.071
1965	11.76	6.19	0.526	1.459
1966	7.48	4.21	0.563	1.658
1967	10.71	4.62	0.431	1.048
1968	12.07	4.51	0.374	0.850
1969	22.41	7.39	0.330	0.716
1970	17.35	5.60	0.323	0.695
1971	19.36	7.90	0.408	0.965
1972	12.44	4.87	0.392	0.910
1973	17.69	4.24	0.240	0.477
1974	20.02	5.38	0.269	0.549
1975	14.85	4.40	0.296	0.620
1976	15.27	6.17	0.404	0.951
1977	25.99	6.11	0.235	0.465
1978	36.12	9.59	0.265	0.539
1979	33.39	7.92	0.237	0.470
1980	25.01	7.15	0.286	0.593
1981	33.39	7.54	0.226	0.444
1982	39.39	9.01	0.229	0.451
1983	32.57	9.80	0.273	0.559

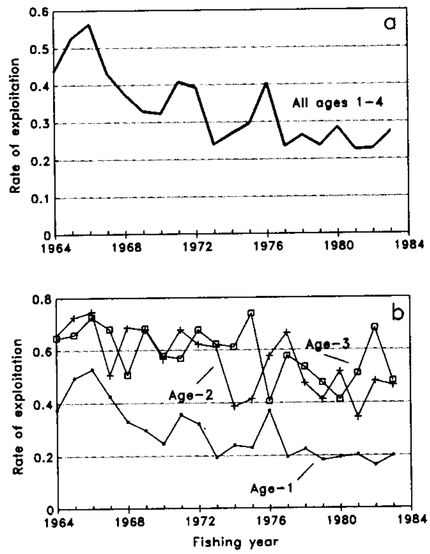

Figure 6.—Annual estimates for Gulf menhaden of (a) population exploitation rates and (b) age-specific exploitation rates (ages 1 through 3), for the period 1964-82.

Table 5.—Estimated number of spawning Gulf menhaden (age 2-4 females) that produced a year class, estimated egg production from the spawning stock, and estimated numbers of recruits to age-1 by year classes, 1964-82 (Vaughan, 1987).

Year class	Spawners[1] Numbers in billions	Spawners[1] Number of eggs in trillions	Number of recruits to age-1 in billions
1964	3.24	38.6	13.36
1965	2.13	24.4	8.26
1966	1.59	16.1	13.20
1967	0.90	10.3	13.88
1968	2.02	22.4	26.94
1969	2.56	31.6	17.46
1970	5.38	55.6	21.27
1971	4.23	54.4	12.51
1972	3.88	45.5	20.69
1973	2.60	32.9	21.21
1974	5.14	74.2	13.96
1975	5.59	88.1	16.31
1976	3.80	58.9	31.23
1977	2.98	39.4	39.81
1978	7.74	80.6	33.82
1979	10.14	125.2	23.14
1980	9.79	125.2	37.46
1981	6.50	69.2	41.79
1982	10.06	103.8	31.01

[1] Spawners (age 2 and older) present on 1 January.

mid-April through mid-October for the reduction fishery.

Population size (age-1 and older at the beginning of the fishing season in April) ranged from 7.5 billion menhaden in 1966 to 39.4 billion fish in 1981 (Table 4). Population size was low between 1964 and 1968 (averaging 10.7 billion menhaden) when landings were low (averaging 384,000 t), generally higher but more variable between 1969 and 1977 (averaging 15.5 billion menhaden) and similar with landings (averaging 547,000 t), and since 1978 generally high (averaging 33.3 billion menhaden) during a corresponding period of high landings (averaging 772,000 t). Recent landings have dropped significantly from 894,000 t in 1987, to 624,000 t in 1988 and to 570,000 t in 1989 (Smith, 1991). However, these analyses are always retrospective and have an inherent time lag. The last estimate of population size is for 1983 and more recent estimates will be included in the next stock assessment.

As with Atlantic menhaden, exploitation rates are valuable for assessing short-term losses to the Gulf menhaden stock (Fig. 6). Population exploitation rate (based on age-1 and older fish) has declined from an average of 47% between 1964 and 1968 when landings and population size were low, to an average of 32% between 1969 and 1977 when intermediate levels of landings and population size were occuring, and finally to an average of 25% since 1978 when landings and population size were large. A general decline is also noted both in the age-specific exploitation rates with fishing year. This decline in population exploitation rate, in part, represents the large increase in population size compared to relatively smaller increases in landings. Average exploitation rates (1964-83) were about 27% for age-1 Gulf menhaden and about 55% for age-2 and age-3 menhaden. Annual natural mortality averaged about 54% for age-1 Gulf menhaden and about 38% for age-2 and age-3 menhaden, although, in the absence of fishing, annual natural mortality losses would be about 67% for all ages.

Spawning is considered to peak about 1 January and coincides with the calendar year used in virtual population analysis for Gulf menhaden. Spawners (age 2 and older on 1 January) ranged between 0.9 billion Gulf menhaden in 1967 and 11.9 billion menhaden in 1983 (Table 5). Low spawning stock size was the rule from 1964 to 1968 (averaging 1.9 billion menhaden), low to moderate spawning stock size prevailed from 1969 to 1977 (averaging 4.0 billion menhaden), and generally high spawning stock size from 1978 to 1982 (averaging 9.4 billion menhaden). Recruits to age-1 on 1 January ranged from 8 billion in 1966 to 42 billion in 1982 with the three highest recruitment years for the study period (1964-82) being the 1978, 1981, and 1982 fishing years (1977, 1980, and 1981 year classes). Recruits to age-1 averaged 15.1 billion for the period 1964 through 1968, 21.6 billion for the period 1969 through 1977, and 33.4 billion since 1978. The cause for this growth in the Gulf menhaden population is unknown. The general subsidence along the Gulf of Mexico, especially along the coast of Louisiana, may provide increased nutrients for young Gulf menhaden, but Klima[1] suggests that there may be an upper limit to this enhancement phenomenon, followed by a crash in productivity.

Since 1964, the proportion of age-2 spawners to the spawning stock has been fairly consistent, ranging between 82

[1]Klima, E. 1988. In draft minutes. 39th Annu. Meet., Gulf States Mar. Fish. Comm., Ocean Springs, Miss.

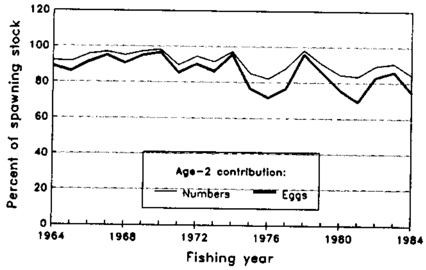

Figure 7.—Contribution of age-2 spawners to total spawning stock (numbers) and to total egg production (eggs) of Gulf menhaden for fishing years, 1964-84.

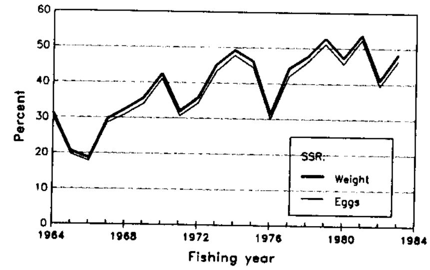

Figure 9.—Equilibrium spawning stock ratio in weight and index of egg production for Gulf menhaden for fishing years, 1955-83.

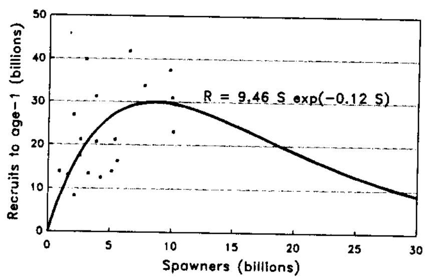

Figure 8.—Numbers of Gulf menhaden recruits (R) plotted against numbers of spawners (S) for year classes, 1964-82. Curve represents the fitted Ricker function $R = \alpha S \exp(-\beta S)$.

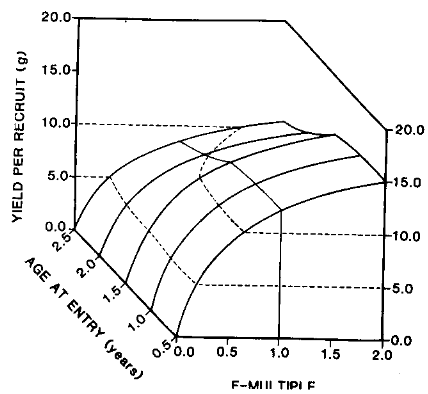

Figure 10.—Yield-per-recruit isopleth diagram for Gulf menhaden using average conditions of growth and fishing mortality for the period 1978-85.

Table 6.—Estimates of yield-per-recruit (*g*) for Gulf menhaden for each fishing year from 1964 through 1983, and for two sets of mean conditions (1978-85 and 1964-85 fishing years). Estimates are presented for two ages at entry (0.5 and 1.25 years) and three *F*-multiples (0.4, 1.0, and 1.6) (Vaughan, 1987).

Fishing year	Age at entry		*F*-multiple		
	0.5	1.25	0.4	1.0	1.6
1964	17.2	17.1	11.8	17.2	19.4
1965	18.0	18.0	13.2	18.0	19.7
1966	18.6	18.6	14.1	18.6	20.3
1967	17.0	17.0	11.1	17.0	19.3
1968	17.3	17.3	12.5	17.3	19.3
1969	10.4	10.4	5.8	10.4	13.4
1970	15.3	15.3	9.6	15.3	18.1
1971	17.5	17.5	12.4	17.5	19.5
1972	15.7	15.7	11.1	15.7	17.3
1973	15.1	15.1	10.2	15.1	17.5
1974	16.3	16.3	9.6	16.3	19.8
1975	16.5	16.5	10.9	16.5	19.2
1976	18.6	18.6	11.9	18.6	21.1
1977	19.3	19.3	13.2	19.3	21.4
1978	14.0	14.0	8.3	14.0	16.8
1979	13.4	13.4	8.3	13.4	16.2
1980	15.4	15.4	9.3	15.4	18.3
1981	10.2	10.2	5.8	10.2	12.4
1982	6.9	6.9	3.9	6.9	9.2
1983	13.6	13.6	8.5	13.6	16.1
			Mean conditions		
1978-85	12.2	12.2	7.9	12.2	14.2
1964-85	15.8	15.8	10.6	15.8	18.1

and 98% in numbers (Fig. 7). Since the mid-1970's, the contribution of age-2 spawners to the spawning stock has averaged about 88% in numbers. As with Atlantic menhaden, after fitting the Ricker curve to Gulf menhaden spawner and recruit data, considerable unexplained variability remains due to environmental conditions or measurement error (Fig. 8). Again, these relationships are statistically significant, so that future recruits do depend to some extent on the size of the spawning stock which produced them, but the large scatter suggests that environmental factors are probably more important in controlling recruitment success or failure.

Contrary to the equilibrium spawning stock ratios obtained annually for Atlantic menhaden, those obtained annually for Gulf menhaden (both biomass and index of egg production) have been generally much larger (20-50%) and with an upward trend (Fig. 9). The index of egg production for Gulf menhaden is based on the egg-length relationship provided in Lewis and Roithmayr (1981). The lowest values were obtained from estimated fishing mortality rates from the 1965 and 1966 fishing years, the highest values were obtained from estimated fishing mortality rates from the 1981 fishing year. These results are not surprising given the decline in F shown in Figure 5, both for all ages 1-4 and especially for age-1. However, with the high natural mortality ($M = 1.1$) for Gulf menhaden and short lifespan (about 4 years), a sudden turnaround in recruitment could still present problems to the fishery.

A yield-per-recruit isopleth shows gains and losses of yield-per-recruit as a function of fishing mortality rate or age-at-entry to the fishery (Fig. 10). Overall yield-per-recruit of Gulf menhaden, for the age at entry of 1.25 years (or 0.5 year) and F-multiple of 1.0 has shown no trend since 1964 with an average of 15.8 g for the period 1964-85 and an average of 12.2 g for the period 1978-85 (Table 6). Yield-per-recruit could actually be increased with higher rates of fishing, as maximum biomass is obtained at age 1.5 years and the rate of natural mortality is quite high. However, attempts to increase yield-per-recruit could have severe consequences: Results from population simulation studies by Nelson and Ahrenholz (1986) and Vaughan (1987) indicate that recruitment overfishing is likely to occur at F-multiples greater than 1.5 for 1978-85 mean conditions.

Estimates of MSY from surplus production models continue the upward trend noted in Vaughan et al. (1986). Chapoton (1972) obtained an estimate of MSY of 430,000 t for the 1946-70 period, Schaaf (1975) obtained an estimate of 478,000 t for the 1946-72 period, Nelson and Ahrenholz (1986) obtained estimates ranging from 540,000 to 640,000 t for the 1946-79 period, and more recently Vaughan (1987) obtained estimates ranging from 620,000 to 825,000 t. The primary biological concern raised by stock assessment scientists is that the nature of the descending limb on the surplus production model can only be determined accurately if landings exceed the current MSY for several years. If the descending limb were steep, heavy fishing could put the stock at greater risk. The Pella and Tomlinson (1969) model, estimated from Gulf menhaden catch and effective effort data, has a flat descending limb (Vaughan, 1987).

Estimates of MSY range from 620,000 to 700,000 t based on surplus production models (landings and fishing effort data from 1946-85 fishing years), and from 705,000 to 825,000 t based on population simulation models (using Ricker spawner-recruit relationships based on 1964-82 year classes) (Vaughan, 1987). The latter range of estimates for MSY is probably more indicative of the average landings that could have been removed from the Gulf menhaden stock during the period from which data were obtained (1964-85 fishing years), given the limitations in adjusting the fishing effort (restricted to 1964-83 fishing years) used in surplus production models and the firmer biological basis for the population simulation approach. Our major concern was that the high landings greater than 800,000 t during most of the 1980's may have been too high.

Management Implications

Both landings and fishing effort have increased dramatically since 1946 (Smith et al., 1987a), with record landings during the 1984 fishing season (982,000 t) and record high nominal fishing effort during the 1983 fishing season (655,800 vessel-ton-weeks). Recruitment to age-1 (on 1 January) varied between 8.3 and 41.8 billion fish (Table 5). Many of the higher values have occurred since 1977, producing greater values for population size and numbers of spawners (Tables 4, 5) and smaller values for exploitation rate (Table 4) in the last decade. Therefore, effective fishing effort has actually declined since the 1960's (Vaughan, 1987). The implication is that the increased landings since 1978 are the result of exceptionally good recruitment (i.e., year classes) and not increased effective fishing effort. Increased geographic availability of Gulf menhaden to the fishery does not seem likely given the closure of reduction plants at the geographic extremes (Nicholson, 1978b), and area and seasonal closures that have been implemented (Christmas and Etzold, 1977; Christmas et al., 1983, 1988).

Historical estimates of maximum sustainable yield (MSY) range from 430,000 to 585,000 t (Chapoton, 1972; Schaaf, 1975; Nelson and Ahrenholz, 1986). With data through the 1984 fishing year, surplus production models produced estimates of MSY from 620,000 to 700,000 t (Vaughan, 1987). Recent recruitment (1976-82) has been excellent and indicates potential yields of about 718,000 t based on a yield-per-recruit analysis. Employing population simulation models with a spawner-recruit relation produced estimates of MSY ranging from 705,000 to 825,000 t. In general, MSY has been exceeded by recent Gulf menhaden landings ranging from 552,600 to 982,800 t during the 1980's. Landings since 1987 have dropped below 800,000 t to 570,000 t in 1989.

The Gulf menhaden is short-lived and has a higher natural mortality than the Atlantic menhaden. Both estimated spawning stock size (Table 5) and spawning stock ratio (Fig. 10) appear healthy, but a rapid change in favorable conditions could alter this picture rapidly, so caution is advised relative to the high F's found and the dependency of the fishery upon very few age groups. Hence, expansion of this fishery by effort or area is not recommended. Concern is therefore raised with the operation of a new reduction plant in 1989 adjacent to a defunct site near Morgan City, La., and expansion of the fishing season for bait fisheries in Florida and Louisiana.

In summary, the Gulf menhaden fishery is currently fully exploited and appears reasonably stable biologically in view of the age composition, life span, and effects of environmental factors. Annual production, fishing effort, and fleet size appear reasonably balanced. Although recent harvests have declined rapidly (from 894,000 t in 1987 to 570,000 t in 1989, it was not considered likely that the high landings (above MSY) obtained during the 1980's could be maintained indefinitely. Landings on the order of 600,000 t are probably more realistic as a long-term average.

Summary

In conclusion, management programs are in place for both Atlantic and Gulf menhaden stocks through the Atlantic and Gulf States Marine Fisheries Commissions. Cooperation is ongoing and seems to work on the Gulf of Mexico Coast, but the Atlantic menhaden plan is not fully implemented. Reevaluation of the management options for the Atlantic menhaden reduction fishery is underway and may replace the variable season closure management recommendation. The expansion of fishing on the spawning stock in New England waters concurrently with increasing fishing pressure on prespawning menhaden off Virginia and North Carolina in the fall prompts concern for maintenance of the Atlantic menhaden resource.

Acknowledgments

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Biological Analysis of Two Management Options for the Atlantic Menhaden Fishery

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ABSTRACT—Biological implications of two managment options (the closed corridor and the recommended shortened season (Option 7) options) for the Atlantic menhaden, Brevoortia tyrannus, *fishery are reported based on purse-seine landings and port sampling data from 1970 to 1984 and captain's daily fishing reports from 1978 to 1982. Large catches of age-0 menhaden raise concern for growth overfishing. Area-specific yield-per-recruit analyses are used to investigate the biological consequences of these management options. The closed corridor option indicates coastwide gains in yield-per-recruit ranging from 0.3 to 7.2% depending on changes in fishing activity with most areas showing gains. The shortened fishing season indicates coastwide gains in yield per recruit ranging from 0.4 to 10.2% depending on fishing year with most geographic areas showing gains. The shortened fishing season option offers the greatest gains when large numbers of young menhaden would be caught late in the fishing year, while gains from the closed corridor option depend on how the fishing fleet responds to that management plan. The shortened season offers greater potential coastwide gains to the fishery, but also may result in greater losses to the North Carolina fall fishery. The analytical approach is applicable to the management of other coastal migratory fish stocks that fall under the Atlantic States Marine Fisheries Commission or other interstate management groups.*

Introduction

The Atlantic menhaden, *Brevoortia tyrannus*, is a euryhaline species found in coastal and inland tidal waters from Nova Scotia, Can., to West Palm Beach, Fla. (Fig. 1) (Reintjes, 1969). They form surface schools in spring and move slowly northward along the Atlantic coast, stratifying by age and size during summer (older and larger fish are generally found farther north) (Nicholson, 1972, 1978). In fall a southern migration begins and by late December or early January surface schools disappear off the Carolinas. Menhaden spawn at sea where the eggs hatch and the larvae are moved into estuaries by ocean currents (Nelson et al., 1977) where they metamorphose and develop into juveniles. In late fall and early winter, the juveniles leave the estuaries and move into large bays or the ocean.

A commercial fishery for Atlantic menhaden has existed since colonial times (Frye, 1978). Modern menhaden reduction plants produce fish meal and solubles, used in poultry and livestock feeds, and oil, used in paints and as an edible oil in Europe and Canada. Atlantic menhaden landings and fishing effort peaked in the late 1950's, declined sharply during the 1960's, and rose gradually during the 1970's and early 1980's (Fig. 2). These landings historically have depended primarily on age-1 and age-2 fish in terms of numbers (Fig. 3). However, large landings of age-3 and age-4 fish in 1961 and 1962, respectively, resulted from the large 1958 year class (note age-1 fish landed in 1959 and age-2 fish landed in 1960). Also, landings of age-0 fish (or "peanuts") exceeded landings of age-1 fish (and age-2 fish as well in 1984) in 1979, 1981, 1983, and 1984. In particular, most Atlantic menhaden landed during the North Carolina fall fishing season are age-0 fish (Fig. 4). The increased dependence of the fishery on age-0 fish (four of the last six years) has increased the concern that growth overfishing may be occurring; that is, Atlantic menhaden are harvested at too young an average age for the full potential harvest from a year class to be attained.

In October 1981 the Atlantic States Marine Fisheries Commission (ASMFC) adopted the Atlantic Menhaden Management Plan (AMMB, 1981). The plan proposed adjustments to fishing activity which included a combination of two approaches: 1) Reducing the catch of age 0, 1, and 2 fish to enhance the survival of menhaden to sexual maturity and increase yield per recruit, 2) reducing the catch of age 3+ menhaden to enhance the number of individuals in the spawning stock. The Atlantic Menhaden Advisory Committee (AMAC) developed a series of management options (actions) for the Atlantic Menhaden Implementation Subcommittee (AMIS) (AMAC, 1982) which were directed at increasing yield per recruit through protection of prerecruit menhaden via area closure, season closure, mesh size limit, or effort reduction. Detailed yield-per-recruit analyses are presented for the closed corridor option and the shortened season management option (Option 7) preferred by AMIS/AMMB.

The closed corridor management option would prohibit purse-seine fishing in an area extending from the beach to 1 mile offshore from Cape Henry, Va., to Cape Fear, N.C., during the period November through January (AMAC, 1982). The intent of this option was to protect a significant fraction of age-0 Atlantic menhaden ("peanuts") thought to occur predominantly within the 0-1 mile zone as they migrate south during the North Carolina fall fishery. As proposed, the option did not address inside waters (rivers and sounds).

Seven season options were investigated (AMAC, 1982), ranging from a curtailment of the fishing season by 1

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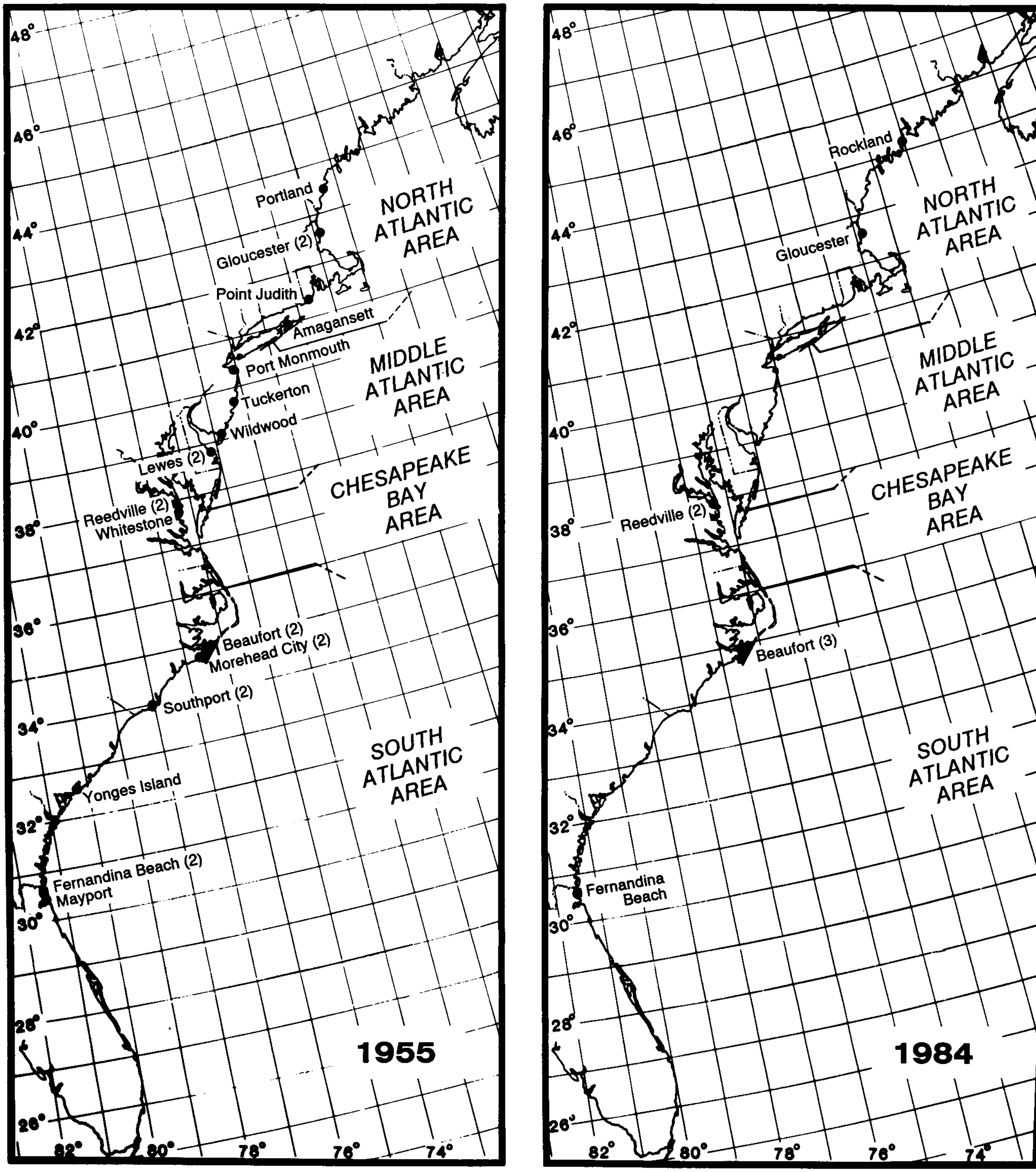

Figure 1.—Geographic fishing areas for the Atlantic menhaden purse-seine fishery, and landing ports for 1955 and 1984. The number of plants operating at each port is given in parentheses when greater than one.

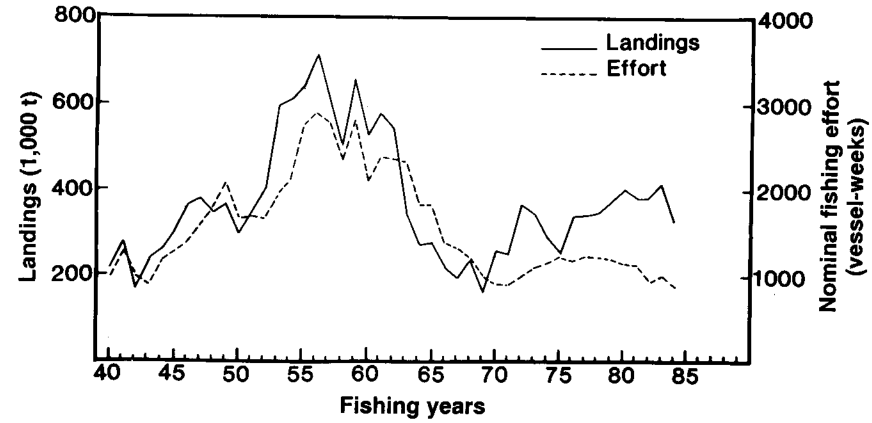

Figure 2.—Catch of Atlantic menhaden in thousands of metric tons and fishing effort in vessel weeks from 1940 to 1984.

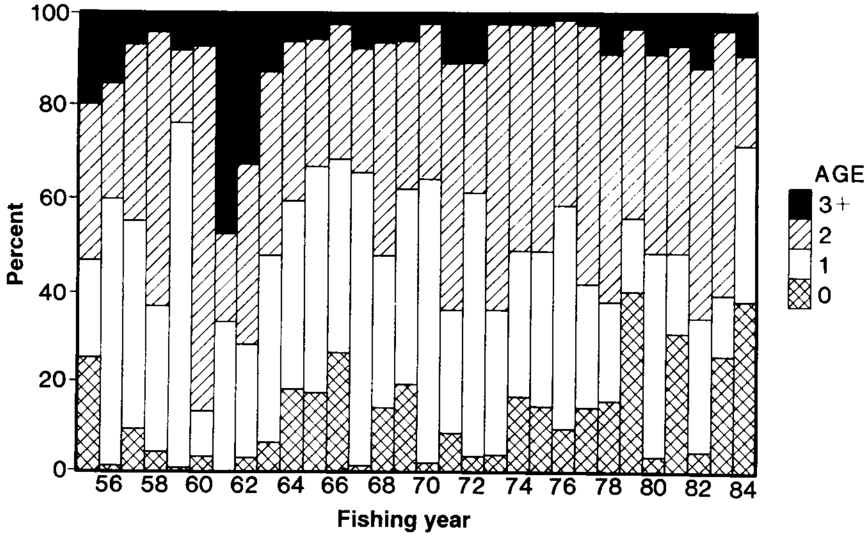

Figure 3.—Contribution in percent of total numbers of Atlantic menhaden landed by age group from 1955 to 1984.

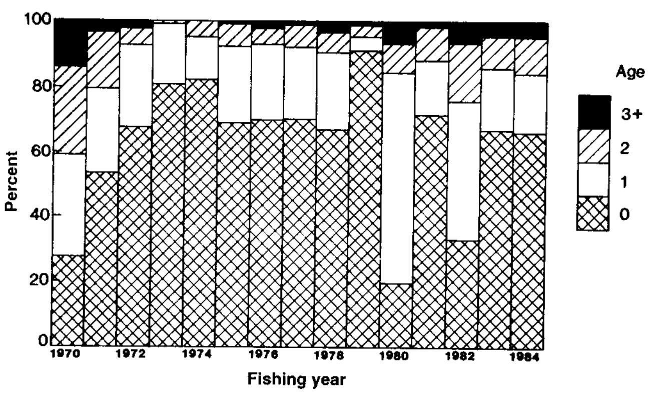

Figure 4.—Contribution in percent of total numbers of Atlantic menhaden landed in the North Carolina fall fishery (Area 5) by age group from 1970 to 1984.

month in a single geographic area (Option 1) to 1 month in all four geographic areas (Option 7). In May 1982, the Atlantic Menhaden Management Board (AMMB) approved a reduction of the fishing season in each reporting area by 4 weeks to be effective in 1983 (Option 7). Proposed opening and closing by week ending dates (Saturday) were:

	Opening Period	Closing Period
North Atlantic	5/17 - 5/23	10/04 - 10/10
Middle Atlantic	5/17 - 5/23	10/11 - 10/17
Chesapeake Bay	5/17 - 5/23	11/08 - 11/14
South Atl. and N.C. fall fishery	4/12 - 4/18	12/13 - 12/19

As of April 1987, six of the 15 member states of the Atlantic States Marine Fisheries Commission (ASMFC) have adopted the approved shortened season management option in compliance with the coastwide Atlantic menhaden fishery management plan. Because of the migratory nature of Atlantic menhaden and multiple jurisdiction of the Atlantic coastal states, it is necessary to consider the differential effect of fishing on different components of the stock. This paper compares two major management options considered by the AMMB in terms of the relative gains in yield per recruit across geographic areas. This approach would be applicable to other highly migratory fish stocks that fall under interstate jurisdiction or the jurisdiction of several councils such as striped bass or weakfish.

Methods

The Beaufort Laboratory of the NMFS Southeast Fisheries Science Center has maintained records of all daily menhaden vessel landings and fishing activity since 1955. Port sampling of catches for weight, length, and age composition are used in conjunction with vessel landings to estimate number of fish landed at each age by plant and area, to determine growth rates, and to estimate fishing mortality (Ahrenholz et al., 1987; Smith et al., 1987). Captain's daily fishing reports, maintained since 1978 on the Atlantic coast, contain specific information about individual purse-seine sets, such as location and distance from shore. An overview of the life history and stock structure of the Atlantic menhaden is presented in Ahrenholz et al. (1987).

June and Reintjes (1959) divided the Atlantic coast into four geographic fishing areas and one temporal fishing area (Fig. 1) for purposes of summarization and analysis. A change in boundary line between the South Atlantic and Chesapeake Bay areas was reported by Nicholson (1975). The divisions are the North Atlantic Area, the Middle Atlantic Area, the Chesapeake Bay Area, the South Atlantic Area, and the North Carolina fall fishery. Historically, the North Carolina fall fishery takes place from Cape Hatteras, N.C., south to the southern border of North Carolina. It begins between the last week of October and the second week of November, depending on the arrival of migratory menhaden from more northerly waters, and lasts to the end of February of the next calendar year, although fishing usually stops by mid-January. For standardized data summary, we use the week which ends (on Saturday) between 8 November and 14 November as the first week of the North Carolina fall fishery.

Closed Corridor Option

The analysis of this option uses estimates of fishing mortality and growth in Ahrenholz et al. (1987) and methods presented in Vaughan (1985). The North and Middle Atlantic fishing areas were combined, and the North Carolina fall fishery was split into three areas: 1) Inside waters including bays and sounds, 2) closed corridor (0-1 mile offshore), and 3) outside waters greater than 1 mile offshore. Quarters of the fishing year were adjusted so that the fourth quarter would coincide with the North Carolina fall fishery and the period of the closed corridor. Quarters began on 1 March, 24 May, 16 August, and 8 November.

Three types of data are used in the following analyses: Vessel landings, port sampling, and captain's daily fishing reports (CDFR). The intersection of the port sampling data base, containing information on the age of the fish, and the CDFR's, containing information on set size and distance from shore, can be used to obtain estimates of the landings in numbers at age for inside waters, the proposed closed corridor (0-1 mile), and outside waters (>1 mile) during the North Carolina fall fishery. Availability of CDFR's from the North Carolina fall fishery is incomplete. Thus, we must assume that the matched data set (i.e., intersection of port sampling and CDFR data sets) adequately describes the catch from Cape Henry, Va., to Cape Fear, N.C., during the North Carolina fall fishery. About 10% of the landings in Virginia after 8 November were caught in the closed corridor area; in biomass this was equal to about 2% of the landings from the North Carolina fall fishery. Over 99% of the landings at North Carolina plants after 8 November were caught between Cape Henry and Cape Fear. Our analysis also assumed that reported catches equal landings and that estimates of catches in numbers at age from inside, closed corridor, and outside waters between the capes during the North Carolina fall fishery could be restricted to North Carolina plants.

Estimation of growth in weight by age and area used the weight (or cubic) version of the von Bertalanffy (1938) growth equation. The port sampling data base for fishing years 1978-82 provided estimates of weight at age for the North Atlantic, Middle Atlantic, Chesapeake Bay, and South Atlantic fishing areas by averaging across fishing years; the estimates of weight for the North and Middle Atlantic areas were then averaged. Comparable estimates of weight at age for the three areal divisions of the North Carolina fall fishery were obtained using the matched data from port sampling and CDFR's. Mean weights at age were also computed for the entire fishery (coastwide) using catch in numbers at age as the weighting factor for each area. Estimates of weight at age at the start of each quarter were generated from estimated parameters in Vaughan (1985: Table 8).

Sensitivity of our conclusions to variability in estimated instantaneous fishing mortality rates was investigated by selecting minimum and maximum estimates of instantaneous fishing mortality rates for each age in quarters from the smallest and largest annual values of the instantaneous fishing mortality rate, respectively (Vaughan, 1985: Table 6). Yield-per-recruit analyses depend on these sets of age-specific mortality rates. Four sets of yield-per-recruit analyses are made: 1) No implementation of the closed corridor management option (used as the base data for comparisons), 2) closed corridor option implemented and no shift of fishing effort from the closed corridor to any other fishing area (Hypothesis I), 3) all fishing effort in the closed corridor redirected to outside waters (>1 mile) (Hypothesis II), and 4) all fishing effort is proportionally divided between the inside waters and outside waters (Hypothesis III). A constant relationship between fishing effort and catch per unit of fishing effort within the same quarter of any given fishing year (i.e., 1978-82) had to be assumed to evaluate the hypotheses. The assumption appears tenable when comparing catches within any given geographic area and season (e.g., North Carolina fall fishery), but is less so across major geographic areas or seasons. Under Hypothesis II all fishing effort is redirected to outside waters, thus fishing effort for the closed corridor simply is multiplied by catch per unit effort for outside waters to estimate catch from outside waters. Hypothesis III divides fishing effort for the closed corridor among inside and outside waters proportional to the catch in numbers for the two areas, and when multiplied by their respective catch per unit effort yields catch. The ratio of these extra catches at age from inside or outside waters to the total catch from the closed corridor allows calculation of the instantaneous fishing mortality rate from the closed corridor that can be applied to inside or outside waters.

Shortened Season Option (Option 7)

The analysis of this option was performed as an adjunct to an updated stock assessment of Atlantic menhaden (Vaughan and Smith, 1988). The fishing year was divided into four approximately equal periods beginning 1 March, 1 June, 30 August, and 30 November, for which a given fishing year extends to the end of February of the following calendar year. Fork lengths at age are arranged quarterly by cohort (1970-81) and fit by area and coastwide to the von Bertalanffy (1938) growth equation to determine growth rates. Weight is determined from length by an allometric relationship. Observed length and weight data are assumed to represent the midpoint of a quarter, calculated weights and lengths represent values at the beginning of each quarter, and are used in yield-per-recruit analyses.

Quarterly virtual population analysis (VPA) for all year classes from 1970 through 1981 provided estimates of population size at the start of each quarter and quarterly fishing mortality rates for each fishing year 1976 through 1981 (Vaughan and Smith, 1988). Estimates of population size at age 0.5 were made for year classes 1976 through 1981 based on differing assumptions as to the catch of age-0 menhaden versus the landings of age-0 menhaden which are sampled. The sensitivity of our conclusions to underestimation of age-0 menhaden in the catches was investigated by conducting four sets of quarterly virtual population analyses. In these analyses the number of age-0 menhaden estimated in the landings were multiplied by 1 (base), 1.5, 2, and 4 to reflect increasing underestimation of age-0 menhaden in the landings (age-0 multiplicative factor). One reason for raising this issue is the statement "[i]t is generally acknowledged [that] the fishing process will sometimes kill additional numbers of small fish" (AMAC, 1982). Furthermore, Chester (1984) demonstrated that in the North Carolina fall fishery, when most age-0 fish are landed, there is a significant bias towards underestimating the numbers of age-0 fish in the landings. This uncertainty was felt to be most critical in our analysis of the potential gains from Option 7.

No change was made in the growth rates with and without Option 7 for the yield-per-recruit analyses. Fishing mortality rates were recalculated from a virtual population analysis approach. All fish landed after the closing date for each fishing year were subtracted from the total landings by area and season. Assuming the same population size at age at the beginning of the quarter during which the closing date occurred, new exploitation rates were calculated, from which coastwide instantaneous fishing mortality rates (F) were calculated iteratively (Ricker, 1975):

$$F=u(F+M)/(1-\exp(-(F+M))), \quad (1)$$

where exploitation rate (u) and natural instantaneous mortality rate ($M=0.45$/year) are known. Proportional F's by area were determined as before, except that catches reflected those with Option 7 in place.

Yield-Per-Recruit Analyses

The yield-per-recruit approach evaluates effects of the rates of growth and mortality (including fishing) to determine whether as much yield is obtained from the fishable population given the observed number of recruits (Ricker, 1975). If the number of recruits is constant from year to year and the other parameters do not change, then total yield from a cohort equals the annual yield from all cohorts present. Recruitment to age-1 for Atlantic menhaden has been relatively constant during the period 1976-81, ranging from 4.3 to 6.9 billion fish, compared to an historical range of 1.4-14.8 billion fish (Vaughan and Smith, 1988).

The computer program MAREA (Epperly et al., 1986) is modified from a multiple-gear extension (MGEAR) (Lenarz et al., 1974) of the Ricker-type yield-per-recruit model to accommodate a multiple area fishery. Ricker (1975) subdivided the exploited phase into segments during which mortality and growth rates can be assumed constant (e.g., quarterly). The effects of varying instantaneous natural and fishing mortality rates during the fishable life span and any general growth pattern can easily be assessed. Total equilibrium yield per recruit would be the sum of the yield in each segment over the total segments in the fishable life span. However, since equilibrium is unlikely to occur, the use of equilibrium yield per recruit is useful only for comparing the productivity of the stock under different exploitation regimes. Although density-dependent growth during the first year of life has been demonstrated in Atlantic menhaden, length at age beyond the first year is independent of population size (AMMB, 1981; and Reish et al., 1985).

Results

Yield-per-recruit analysis (Fig. 5) suggests that the fishery is harvesting the Atlantic menhaden stock at too young an age, and shows that increased age at entry increases potential yield from the stock. Estimates of annual yield per recruit are made to observe the hypothetical change in equilibrium yield per recruit given implementation of a management option during that fishing year. For the shortened season (Option 7), averaging over several fishing years would tend to mask year-to-year variability in gains in yield per recruit due to temporal variations in migration of age-0 Atlantic menhaden (i.e., recruitment or availability of juveniles to fishing gear).

Closed Corridor Option

Yield-per-recruit analyses (MAREA) were conducted for the base condition (no implementation of the closed corridor management option) and three hypothetical scenarios (Hypotheses I-III) for redeployment of fishing effort from the closed corridor. Each situation (base condition and three hypothetical scenarios) were repeated for minimum, mean, and maximum estimates of instantaneous fishing mortality rates (Table 1) to assess the sensitivity of the conclusions to variability in estimates of the instantaneous fishing mortality rates.

Largest coastwide gains in yield per recruit are from no redeployment of fishing effort from the closed corridor (1.3-7.2%, Hypothesis I) and the least gains are from redeployment of fishing effort to both inside and outside waters (0.3-3.6%, Hypothesis III) (Table 1). The Chesapeake Bay area makes the largest contribution to yield per recruit (without regulation) and the next largest is from the South Atlantic area, excluding the North Carolina fall fishery. Some of the gains that would otherwise accrue are lost when effort is redirected to outside waters (Hypothesis II) or to both inside and outside waters (Hypothesis III), due to the additional catches by the redirected fishing effort. Inside waters contribute the next largest catch in numbers of age-0

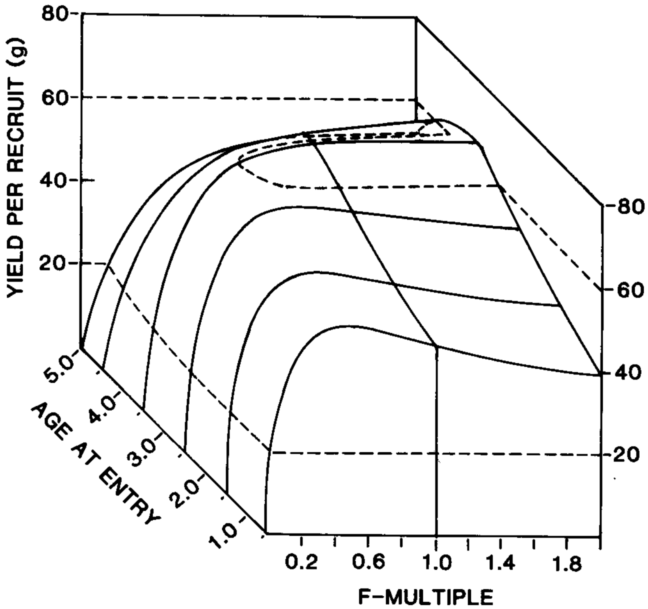

Figure 5.—Overall yield per recruit of Atlantic menhaden under current conditions (F-multiple of 1.0 and age at entry of 0.5) using average fishing mortality values by quarter for the 1981 fishing season.

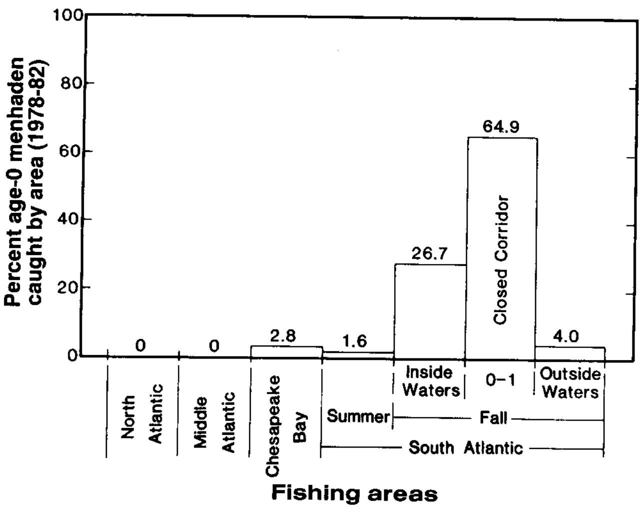

Figure 6.—Proportion of age-0 Atlantic menhaden caught by fishing areas used on the "Closed Corridor" analyses for fishing years 1978-82.

Table 1.—Percent change in yield per recruit by area and for the entire Atlantic menhaden purse-seine fishery for three hypothetical scenarios based on the "Closed Corridor" management option compared to the fishing regime for the 1978-82 fishing years. Analysis performed for three levels of instantaneous fishing mortality rates (minimum, mean, and maximum).

Area	Yield per recruit (g)	Change (%) hypotheses[1] I	II	III
Minimum fishing mortality assumed				
North/Middle Atlantic	5.41	9.4	6.8	1.7
Chesapeake Bay	25.38	14.3	4.7	1.2
South Atlantic	9.13	6.9	5.1	1.3
N.C. fall fishery	3.12	-66.0	-47.1	-15.7
Inside waters	0.71	5.6	4.2	193.0
Closed corridor	2.11	-100.0	-100.0	-100.0
Outside waters	0.30	3.3	203.3	83.3
Entire fishery[2]	45.66	1.3	1.0	0.3
Mean fishing mortality assumed				
North/Middle Atlantic	7.69	23.5	17.0	4.2
Chesapeake Bay	25.08	13.8	10.1	2.5
South Atlantic	9.70	14.7	10.8	2.7
N.C. fall fishery	5.33	-63.2	-45.0	-15.8
Inside waters	1.26	14.3	10.3	186.5
Closed corridor	3.61	-100.0	-100.0	-100.0
Outside waters	0.46	13.0	234.8	91.3
Entire fishery[2]	50.29	6.0	4.4	1.1
Maximum fishing mortality assumed				
North/Middle Atlantic	5.92	27.4	19.6	5.1
Chesapeake Bay	25.06	16.2	12.5	3.0
South Atlantic	9.51	17.4	12.7	4.1
N.C. fall fishery	5.54	-63.4	-44.9	2.5
Inside waters	1.29	14.7	10.9	255.0
Closed corridor	3.78	-100.0	-100.0	-100.0
Outside waters	0.47	17.0	244.7	134.0
Entire fishery[2]	48.38	7.2	5.3	3.6

[1] Hypotheses are defined as follows: I, no redistribution of fishing effort from closed corridor; II, all fishing effort from closed corridor is redeployed into outside waters; and III, all fishing effort from closed corridor is proportionally redeployed to inside and outside waters.
[2] The sum of areas is slightly different from the entire fishery due to the nature of the yield-per-recruit program (MAREA), which calculates yield per recruit for individual areas and then calculates overall yield per recruit instead of summing the areas. Thus, differences are due primarily to using a separate set of weights derived from the entire fishery.

menhaden (27%) after the closed corridor (65%) (Fig. 6), thus redirecting effort only to outside waters (Hypothesis II) will result in higher yield per recruit than redirecting some of that effort to inside waters (Hypothesis III). Further, the higher catch per unit of fishing effort for inside waters compared to outside waters (for the matched data set) also contributes greater gains in yield per recruit from Hypothesis II than from Hypothesis III.

Shortened Season Option (Option 7)

Yield-per-recruit analyses (MAREA) were conducted for Option 7 for fishing years 1976-81 and for four levels of the age-0 multiplicative factor (f = 1.0, 1.5, 2.0, and 4.0) (Table 2). Concurrent with these analyses, the total closure of the North Carolina fall fishery was addressed for comparative purposes only. Assuming the estimated landings of age-0 fish accurately reflect age-0 fish caught or killed (f = 1.0), then coastwide gains accruing from Option 7 range from 0.4% in 1981 to 10.2% in 1979. Although large numbers of age-0 fish were estimated as landed in both fishing years (Fig. 7), most age-0 menhaden (94%) landed in 1979 were caught after the proposed closing date compared to only 3% caught in 1981 after the closing date. Gains in yield per recruit are almost identical with a closed North Carolina fall fishery in

1979 and 1981 (Table 2). With large numbers of age-0 menhaden caught in 1983 and 1984 (68% for both years after proposed closure), large gains in yield per recruit for these fishing years would result. Since few age-0 menhaden were landed in 1980 (and in 1982), computed gains in yield per recruit would be small even when compared to a total closure of the North Carolina fall fishery (Table 2). The annual estimates of yield per recruit are not necessarily intended to represent absolute yield per recruit attainable. They permit interyear comparisons to show how timing of the migration patterns of age-0 menhaden would effect the gains accrued from the Option 7 management strategy.

With increasing underestimation of age-0 fish caught or killed (e.g., increasing age-0 multiplicative factor), the gains in yield per recruit from Option 7 also increase because greater numbers of age-0 fish would actually have been saved (Table 2). For an age-0 multiplicative factor of 4.0, a dramatic increase to a 33.8% gain is noted for the 1979 fishing year, and to a 9.5% gain for the 1976-78 fishing years. Gains from Option 7 would have been negligible for the 1980 and 1981 fishing years since small percentage of age-0 fish were in the landings after the proposed closing date.

Changes in yield pér recruit also vary with fishing area (Table 3). Generally all areas experience a gain in yield per recruit except the North Carolina fall fishery. Gains to the North Atlantic area mostly benefit small plants in Gloucester, Mass., and Rockland, Me. (Fig. 1). Two large plants in Reedville, Va., benefit from gains in yield per recruit to all geographic fishing areas, since they land fish caught between Cape Hatteras, N.C., and Rhode Island. The North Carolina and Florida plants show a gain during the summer fishery (South Atlantic area), but the North Carolina plants suffer losses during the North Carolina fall fishery. To the extent that North Carolina vessels fish in other areas, those plants can benefit from gains in yield per recruit to those areas. For example, a North Carolina vessel caught fish in the Middle Atlantic area during 1984, so some gain in yield per recruit for the Middle Atlantic area would have accrued to the South Atlantic area.

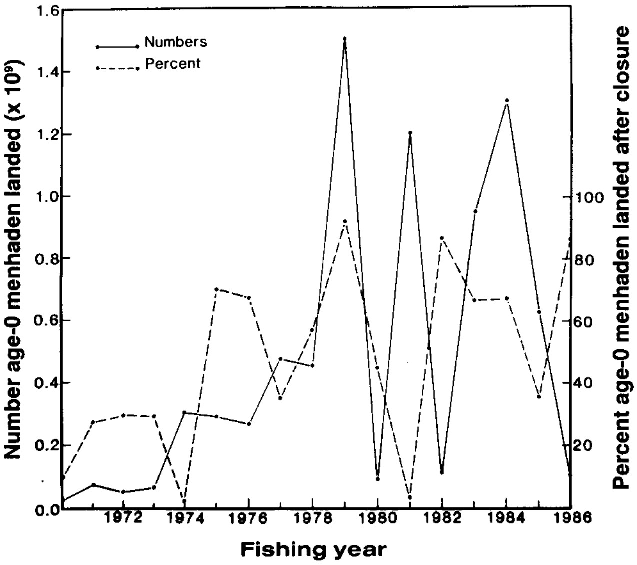

Figure 7.—Number of age-0 Atlantic menhaden landed and percent landed after "Shortened Season" closure for fishing years 1970-86.

Table 2.—Yield per recruit (g) from the entire Atlantic menhaden fishery for the fishing years 1976-81, and percent change resulting from a "Shortened Season" by 1 month (Option 7) or closure of the North Carolina fall fishery. Each comparison is made for four levels of the age-0 multiplicative factor described in text to adjust for catches of age-0 above those estimated from landings.

Age-0 multiplicative factor	Fishing year 1976-78	1979	1980	1981
Entire fishery (Base yield per recruit)				
1.0	58.62	53.04	53.84	45.95
1.5	57.34	50.79	53.60	44.36
2.0	56.15	48.85	53.38	42.98
4.0	52.12	43.23	52.49	38.77
Option 7, Shortened season (% change)				
1.0	+2.9	+10.2	+0.6	+0.4
1.5	+4.0	+14.8	+0.8	+0.5
2.0	+5.1	+19.1	+1.0	+0.6
4.0	+9.5	+33.8	+1.8	+1.0
Closed North Carolina fall fishery (% change)				
1.0	+5.5	+10.5	+1.8	+10.6
1.5	+7.8	+15.4	+2.2	+14.2
2.0	+10.0	+19.9	+2.6	+17.5
4.0	+18.3	+35.4	+4.2	+29.0

Table 3.—Percent change in yield per recruit by fishing areas and for the entire Atlantic menhaden fishery for the 1976 through 1981 fishing years resulting if the "Shortened Season" option had been in effect. The age-0 multiplicative factor increases the numbers of age-0 menhaden assumed caught or killed by the purse-seine fishery. (SA + NCFF combines South Atlantic and North Carolina fall fishing areas.)

Fishing area and year(s)	Percent change for age-0 multiplicative factor 1.0	1.5	2.0	4.0
1976-78 Fishing years				
North Atlantic	18.1	20.1	22.4	31.6
Middle Atlantic	2.5	4.4	6.4	14.4
Chesapeake Bay	5.2	7.3	9.3	17.5
South Atlantic	7.2	9.4	11.5	19.8
N.C. fall fishery	-45.9	-46.3	-46.6	-47.5
SA + NCFF	-8.6	-8.9	-9.2	-10.2
Entire fishery	2.9	4.0	5.1	9.5
1979 Fishing year				
North Atlantic	23.0	32.8	42.7	81.9
Middle Atlantic	2.7	11.2	19.2	52.3
Chesapeake Bay	20.8	30.4	40.1	78.4
South Atlantic	21.2	30.8	40.6	78.7
N.C. fall fishery	-49.7	-55.7	-59.7	-67.3
SA + NCFF	-11.0	-13.4	-15.2	-19.7
Entire fishery	10.2	14.8	19.1	33.8
1980 Fishing year				
North Atlantic	-0.1	0.3	0.6	2.2
Middle Atlantic	6.7	7.3	7.8	9.1
Chesapeake Bay	1.9	2.3	2.6	4.0
South Atlantic	3.7	4.0	4.4	6.2
N.C. fall fishery	-20.4	-20.7	-21.1	-22.1
SA + NCFF	-6.4	-6.5	-6.7	-6.7
Entire fishery	0.6	0.8	1.0	1.8
1981 Fishing year				
North Atlantic	-0.1	0.3	0.4	1.7
Middle Atlantic	1.5	2.2	2.3	3.6
Chesapeake Bay	1.1	1.4	1.6	2.6
South Atlantic	1.2	1.5	1.7	2.7
N.C. fall fishery	-3.0	-2.9	-2.8	-2.7
SA + NCFF	-0.7	-0.6	-0.6	-0.5
Entire fishery	0.4	0.5	0.6	1.0

Management Implications

The Atlantic menhaden fishery has recovered somewhat from the depressed levels during the 1970's, although not to levels attained during the late 1950's when landings åveraged 625,000 t (1955-59 fishing years, Fig. 2). Recent estimates of maximum sustainable yield range from 450,000 to 490,000 t, while recent landings have averaged 364,000 t during the 1976-81 fishing years (Vaughan and Smith, 1988).

The closed corridor option sought to reduce the landings of age-0 menhaden off North Carolina's coast late in the fishing season (Fig. 6). Based on the mean fishing mortality for the period 1978-82, potential gains in yield per recruit for the closed corridor option ranged from 1.1% to 6.0% depending on the hypothesis selected (Table 1). Redeployment of fishing effort to outside waters (Hypothesis II) now appears to be the most likely response of the menhaden purse-seine fleet to implementation of the closed corridor option. Coastwide gains in yield per recruit under this hypothesis range from 1.0 to 5.3%. All areas but the North Carolina fall fishery show a gain in yield per recruit from this option under all three hypotheses. Greatest losses in yield per recruit to the North Carolina fall fishery were under Hypothesis I (63.2-66.0%), and least were under Hypothesis III (gain of 2.5% to a loss of 15.8%). Under Hypothesis II some of the lost landings from the closed corridor can be recouped from outside waters.

The shortened season (Option 7) also sought to reduce the landings of age-0 and other prespawning Atlantic menhaden migrating off Virginia and North Carolina late in the fishing year (Fig. 7). Potential gains from this option range from 0.4 to 10.2% based on historical distribution of fishing mortality depending on the fishing year (Table 2). These annual variations in computed gains in yield per recruit depend primarily on the timing of the coastal movements southward of age-0 menhaden. If more age-0 menhaden are killed than are landed as cited by vessel captains, the gains from Option 7 are even greater, ranging from 0.6 to 19.1% when twice as many age-0 menhaden are killed than landed for the period 1976-81. Gains in yield per recruit accrue to all areas except for the North Carolina fall fishery (Table 3). North Carolina plants will suffer net annual losses even when gains from the South Atlantic fishing area are combined with losses from the North Carolina fall fishery.

Gains in yield per recruit from the closed corridor option depend on the consistency with which age-0 menhaden remain within the 1-mile corridor as indicated by the historical data used in the analyses (Fig. 6). Coastwide gains range more widely for Option 7 than those for the closed corridor option because the former depends both on when age-0 fish become available to the fishery and if the weather permits fishing to continue late in the fishing year. Fishing on age-0 fish during the 1984 fishing year continued into early February 1985 for the first time since the 1950's. We have greater confidence in the predicted gains from Option 7 because of the uncertainty in fishing strategy under the closed corridor option (Hypotheses I-III). Further, Option 7 is more equitable since each fishing area must initially forego 1 month of landings from their traditional fishing seasons. Season options (including Option 7) are easier to enforce than a closed corridor or area wherein distance from shore must be known accurately for enforcement.

No coastwide gains can be accrued in either case unless landings of age-0 menhaden are reduced significantly. Since age-0 fish are landed primarily in the North Carolina fall fishery (96% during 1978-82, Fig. 6), thus a loss in yield per recruit almost always occurs for this fishing area. Losses for the North Carolina fall fishery appear potentially great under both Option 7 (2.8-59.7% for $f = 2$; Table 3) and under the closed corridor option (losses of 44.9-47.1% for Hypothesis II; Table 1).

Obviously, many of the variables and parameters in these analyses have considerable variability. However, sources of potential bias that we believe are most critical to our conclusions are addressed by the use of a range in quarterly F's for the closed corridor option, and by annual MAREA computer runs and the age-0 multiplicative factor for Option 7. Assuming a constant instantaneous natural mortality rate (M) is a standard practice for stock assessments, with variability in M incorporated in F ($Z = M+F$; Ricker, 1975) through virtual population analysis. The intent of these analyses is to demonstrate the direction of changes and their relative magnitudes for critical comparison of the impacts of two management options across geographic areas which are most contentious.

In summary, yield-per-recruit analyses suggest that yields of 376,000 t ($f = 1.0$) to 403,000 t ($f = 4.0$) would have been available compared to an average of 364,000 t for the period 1976-81 if Option 7 had been in place (Vaughan and Smith, 1988). Greater gains are possible by adjusting the F-multiple and age at entry, but devising management schemes that are both enforceable and allow precise protection of young fish are difficult.

Two relevant events occurred during the 1985 fishing year. First, the North Carolina Marine Fisheries Commission adopted a regulation for the menhaden purse-seine fishery that included closure of inside waters and a 1-mile corridor for the entire North Carolina Atlantic coast from 15 January to 15 May. Purse-seine fishing beyond 1 mile is allowed year round off North Carolina. Second, the largest reduction plant normally operating during the North Carolina fall fishery did not fish during 1985. This resulted in a reduction in fishing effort for the North Carolina fall fishery from 112 vessel-weeks in 1984 to 20 in 1985. As a result, fewer age-0 menhaden were landed during this fishing year compared to the previous two years (Fig. 7). Hence, although neither management option is in effect in the North Carolina fall fishery, reduced fishing effort due to economic factors may contribute to an increase in yield per recruit for the near future.

The use of area-specific growth and mortality information were needed because of the highly migratory nature of the Atlantic menhaden and the numerous state jurisdictions across which they migrate. The MAREA computer program (Epperly et al., 1986) was modified from MGEAR (Lenarz et al., 1974) specifically to address this problem with regard to yield-per-recruit analyses. This approach can be applied readily to other highly migratory coastal species such as red drum (Mercer, 1984), weakfish and other sciaenids (Mercer, 1985), and striped bass (Anonymous, 1981), which are caught within several management jurisdictions.

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